PERFORMING THE GALILEO JUPITER MISSION WITH THE LOW-GAIN ANTENNA (LGA) AND AN ENROUTE PROGRESS REPORT

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Abstract

Galileo is now nearing the one-year mark along its three-year direct Earth-to-Jupiter transfer trajectory, having received its final interplanetary gravity assist from Earth on December 8, 1992. Except for its High-Gain Antenna (HGA), Galileo is performing beautifully. There is no longer any significant prospect of deploying the HGA. New flight software and ground software and hardware are being developed to achieve the majority of Galileo's objectives using only its Low-Gain Antenna (LGA). At least 70 percent of the objectives can be achieved including 100 percent of the Atmospheric Entry Probe Mission and the return of thousands of the highest-resolution Galilean satellite images ever planned for the Orbiter Mission. The implementation of the enabling capabilities and the mission plan are described. Also, the results of the second Earth/Moon encounter and the second asteroid (Ida) encounter are summarized.

1. Introduction

Presently, Galileo is about halfway along its now direct Earth-to-Jupiter transfer trajectory, as illustrated in Fig. 1. Galileo's flawless execution of the VEEGA (Venus-Earth-Earth-Gravity-Assist) trajectory was completed with the Earth-2 Gravity Assist on December 8, 1992. Galileo successfully performed its second asteroid encounter with Ida less than two months ago on August 28, 1993.

The Orbiter will release the Atmospheric Entry Probe on July 10, 1995; five months later both spacecraft will arrive at Jupiter on December 7, 1995 such that the Orbiter overflys the Probe to receive and record the data sent from the Probe as it descends in the Jupiter atmosphere. About an hour after this 75-min relay, the Orbiter will initiate its Jupiter Orbit Insertion (JOI) maneuver.

Figure 1 shows when each Orbiter perijove pass/satellite encounter occurs in the orbiter's two-year primary mission. References 1 and 2 provide comprehensive

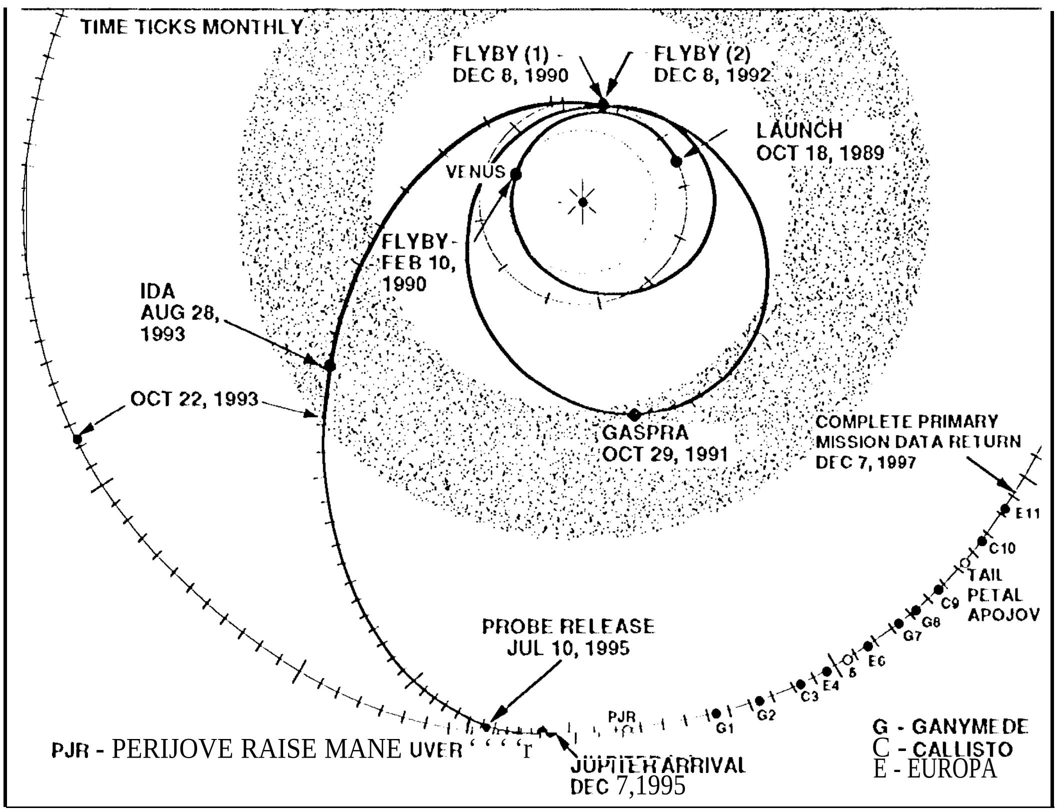

Figure 1. The Galileo VEEGA Trajectory to Jupiter

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descriptions of the Galileo mission, spacecraft, and science payload. Reference 3 presents Project status as of a year ago. This paper foc.uses on Galileo activities over the past year. In addition to performing its second and final Earth-Moon encounter and the Ida encounter this past year, Project Galileo completed its exhaustive campaign to fret the HGA without success and is now well along in implementing the new ground and spacecraft capabilities to perform the mission using the Low-Gain Antenna (LGA). At least 70 percent of the overall mission objectives will be achieved, including 100 percent of the atmospheric Probe mission and the return of thousands of high resolution Galilean satellite images. The spacecraft health and performance arc. excellent.

2. High-Gain Antenna (HGA) Deployment Problem Closeout

Reference 1 gives a detailed description of the HGA and its anomalous deployment scenario. Reference 3 describes the actions taken and those planned as of a year ago to free the stuck ribs. These descriptions arc. highly recommended to those interested in the HGA problem. It is now virtually certain that one or both of the mid-rib-restraint locating pins of three adjacent ribs are stuck in their receptacles on the central tower, thus binding those ribs to the tower and preventing full deployment of any of the other ribs.

After a nearly two-year campaign of spacecraft actions to free the stuck ribs there is no longer any significant prospect of deploying the HGA. The Project is proceeding to perform the Galileo Mission with the. Low-Gain Antenna [his implementation is the central topic of this paper.

From May 1991 through July 1992, spacecraft attitude maneuvers were. performed to thermall y cycle the HGA to produce the maximum possible. relative motion between the ribs and the tower; i.e., between the pins and receptacles. Modeling indicated the possibility of "walking" the pills out of the receptacles in this manner. After the seventh cycle in July 1992, it was clear this tactic would not work,

However, the most aggressive actions were still ahead and associated with Galileo's final perihelion on December 13, 1992. For several months around perihel ion Gal ileo would be near 1 AU from the Sun. For the first time since the anomaly it would be possible to extend the tower to assembly dime.nsiolls and also to "hammer" the deployment ballscrew with maximum torque pulses due. to the. warm temperature at 1 AU.

A short hammering test was successfull y performed on the spacecraft in October 199? to demonstrate the newly designed, non-standard spacecraft sequence for rapidly pulsing the deploy motors on and off. Then on December 28 a warming turn produced maximum tower extension, but no rib released. "The following day over 2,000 pulses were applied. The ballscrew rotated about 1.5 turns before re-stalling after a few hundred pulses. This ballscrew advance was very close to that predicted in ground tests of the spare HGA at JPL. The ballscrew advance is fully con oborated by the 8 deg further deployment of Rib #2 to a deploy angle, of 43 deg as "seen" by the sun gate sensor. Analysis indicates the force in the most loaded of the rib-deploy pushrods was more than doubled to nearly 300 lbs as a result of the ballscrew advance, but most unfortunately this is not enough to break the rib free from the frictional binding in the pin/receptacle interface. Ultimately, over 13,000 hammer pulses were applied between December 29 and January 19 with concentration during thermal transients produced by spacecraft attitude maneuvers. Hammering was also done while the spacecraft was at high spin (10.5 rpm) in March 1993. None of this produced any further ballscrew advance. beyond the re-stall point achieved in the first hammering session of December 29. The Project has now done everything possible to free. the ribs. 'There simply is not enough authority onboard the spacecraft to break the restraint.

3. Earth/Moon-2 Science

Galileo had several major science goals for the second Earth/Moon encounter: 1) cal ibrations and checkouts required by the. instruments to prepare for Jupiter operations, 2) playback of the bulk of the Gaspra data from the tape recorder, 3) lunar observat ions, particularly of the northern polar regions poorly observed from Earth and previous spacecraft, and 4) Earth remote-sensing observations, particularly a multispectral study of a region in the Andes Mountains and searches for polar stratospheric clouds in the Antarctic. Two other special tasks were undertaken: an optical communications experiment designed by researchers in JPL's Tracking and Data Acquisition Office, and a time-lapse sequence of the Moon passing in front of the Earth as seen from the spacecraft.

The instrument Calibrations and checkouts were particularly important due to the High-Gain Ante.nna problem. Priority was given to activities which required high data rates so they would not have to later compete for the very limited downlink on the Low-Gain Antenna in the event the HGA remained stuck. These activities were all successfully carried out, including a very important Mission Sequence Test for the Probe, a complete "rehearsal" of the instrument operations during the descent through the Jovian atmosphere. All the instruments on both the. orbiter and Probe were found to be in excellent health.

The data stored on the tape recorder from the Gaspra encounter were completely played back as the spacecraft approached the Earth and a high-rate downlink became available. These data have give.r] us a relatively complete view of the shape of this unusual body through one rotation (Fig. 2). The data have also allowed Galileo scientists to compare spectral data from the Near-]nfrwed Mapping Spectrometer (NIMS) with multispectral images from the Solid-State Imaging System (SSI) to gain new insights into the chemistry of the asteroid. Preliminary analyses show small, but highly significant changes in the minerals exposed on different parts of Gaspra's surf ace., strengthening the argument that its composition is more similar 10 that of thermally evolved meteorites than the more primitive chondrites. Many of the ideas and [hurries derived from study of Gaspra will be tested as the data from the August 28 lda encounter bc.come avai lable.

Another significant finding was evidence from the magnetometer experiment that the magnetic field in the solar wind was deflected in the vicinity of Gaspra, in a way consistent with Gaspra posse.ssing a significant magnetic moment, in fact similar 10 that found in some magnetized meteorites. Although still tentative, this result too wiii be tested by lhc Ida experiments, where a similar magnetic signature is being searched for in the data.

The lunar data consisted primarily of a series of multispectral image mosaics with significantly higher spatial resolution than the first Earth/Moon encounter data. These data covered the lunar northern polar region and connect with data taken on the Earth-facing hemisphere for comparisons with ground-based data and "ground-truth" from Apollo sample-return sites. '1 'hese data are being studied intensively 10 determine the types of the lava flows present in the poorly studied high latitudes, [tic extent of "crypto-mare" (mare basalts mantled by later ejecta from large basin-forming events), and the relationship of the polar units to such long-standing issues as the origin and extent of what arc. know as the light plains units.

Another lurm-related observation was made by the ultraviolet spectrometer (UVS), which measured very low co ncentrations of atomic hydrogen in the vicinity of the Moon. Later scans of the entire Earth/Moon system produced an ultraviolet image of Earth's extended hydrogen cloud (the "geocorona") being elongated in the. anti-sun direction by radiation pressure. Still a subject of considerabic debate is the possible contribution to these hydrogen clouds by small comets in the vicinity of the Earth which may impa ct the Moon.

Multispectral observations of the Andes Mountains were successfully made. They arc being studied along with J :arth-orbital and ground -truth observations to improve our techniques for studying cloud and ground moisture, and icc and vegetation states 011 our own planet. The NIMS observations of Antarctic stratospheric clouds suggest that such features, which arc important in the ozone destruction cycle, may be present later in the. season more. frequently than had been thought.

The TDA's GOPEX optical communications experiment was also highly successful, demonstrating the capability to detect modulated laser energy from ground stations at

Figure 3. Earth-Moon Conjunction, December 16, 1992, from 6.2 million km.

deep-space ranges for the first time.. Finally, the Earth-Moon conjunction observations resulted in a spectacular view of our home planetary system seen from the perspective of an interplanetary visitor watching the Moon pass in front of the Earth. Figure 3 is a black and white version of a representative frame from a computer-generated color movie of the transit based on 50 color images taken over a 14-hr period about 6 million km outbound from the Earth/Moon system.

4. Spacecraft Performance

4.1 Performance Summary

Aside from the failure of the HGA to deploy, spacecraft health and performance continue to be excellent. Galileo has superbly performed all Trajectory Correction Maneuvers (TCMs), attitude maintenance maneuvers, propulsion maintenance, telecommunications, Probe checkouts, science acquisition, and activities related to the High-Gain Antenna. Since September 1992, Galileo has performed five TCMs, two Probe system checkouts, nine.tc.crl thruster flushing maintenance activities, seventeen attitude control maintenance turns, a host of engineering and science calibration/characterization activities, return of all the Gaspra encounter data and the Earth-2 encounter data, a Galileo Optical Communication Experiment (GOPEX), intensive HGA motor hammer activities following Earth-2, and the Ida encounter. A Radio Relay Antenna (RRA) slew test was performed in April 1993 to characterize the slew performance of the RRA.

The spacecraft also completed several special telecommunications tests, including X-band RF uplink and downlink tests to determine if the asymmetric partially deployed HGA has a usable gain lobe. Other S-band tests were conducted to verify/characterize some of the telemetry design improvements needed to carry out the Galileo mission using the S-band Low-Gain Antenna.

In support of the HGA anomaly efforts, intensive HGA motor pulsing activities were performed from late December 1992 through mid-January 1993. A total of 13,320 motor pulses were executed between December 29, 1992 and January 19, 1993. Each pulse simultaneously applied power to both HGA deployment motors for 266 ms. Pulse trains of 1.25 Hz and 1.875 Hz duty cycles were used.

During the past year the AC/DC bus imbalance continued and the Command and Data Subsystem (CDS) spurious transient bus reset power-on-reset (POR) anomaly recurred (both are discussed in Reference 4). The cause for these anomalies is believed to be slip-ring brush wear debris which builds up and forms conductive paths among Spin Bearing Assembly (SBA) electrical interfaces. Intensive ground tests demonstrated that the debris paths arc cleared with low current levels (less than 100 mA) and consequently there is no threat to the spacecraft.

The following paragraphs brief'iy summarize by subsystem the spacecraft health and performance since September 1992.

4.2 Telecommunications

The health and performance of the telecommunications subsystem equipment is excellent. Aside from the. HGA anomal y, the S-band radio receiver, transmitter, command digital detector and Low-Gain Antenna (LGA) are functioning within specification. Recently in June 1993, the X-band transmitter equipment was powered for the first time since launch to support an HGA downlink characteriz ation test. Al l of the X-band transmitter equipment functioned normally and within predicted values. Several periodically planned telecommunicat ions tests were performed in support of continued routine performance trend analysis. A number of major special tests were also performed to characterize the partially deployed HGA and to collect telemetry performance information to support the Gal ileo mission using the LGA.

An X-band uplink (7167 MHz) test was conducted in March 199310 determine if the asymmetric partially deployed HGA has a usable gain lobe. Test results suggested that a gain lobe about 4 to 7 dB better than the LGA may exist about 1 degree off boresight. Subsequently, in late June, 1993, an X-band downlink (8420 MHz) survey test was conducted. The X-band signal was intermittently detected hy the Deep Space Network (DSN) receiving antenna as the spacecraft was turned about 4 '20 degrees off Iiar[h-line. A detail gain lobe survey was performed every 0.25 degree between O and 4 degrees off boresight. Data analyses of the downlink test arc in process with final results expected late.r this year; preliminary results indicate that no usable gain lobe exists.

Another set of downlink tests were conducted in April and May 1993 using the S-band transmitter hardware. These performance tests were conducted to verify the predicted improvement when using a suppressed carrier modulation technique with the DSN Engineering Model advanced receiver. The test demonstrated that observed performance was near the theoretical predicted value; i.e., about a 5.5 dB improvement was achieved.

During the Earth-2 flyby in December 1992, large (~6 dB) telemetry performance fluctuations were observed, resulting in some data outages. Although some telemetry degradation was expected, the observed performance was worse than expected. Subsequent detailed anal ysis revealed that the degradation resulted from the unique flyby geometry cond i lions which produced telecommunications cone angles up to 130 degrees. At such large angles, metal rods within the LGA tip shade located under [he. LGA cause.d RF multipath interference, thereby disrupting the RF link. As the spacecraft trajectory moved away from Earth and stored sequence attitude-update turns were completed, the telecommunication cone angles decreased and stable telemetry performance returned to near predicted values.

4.3 Power/PYRO

The power/pyro hardware is functioning excellently. Total power output from the Radioisotope Thermoelectric Generators (RTGs) is about one percent below pre-launch predictions. All power electronics control and switching functions continue 10 operate perfectly. On the Earth-2 approach trajectory, the Probe Power Interface Unit (PPIU) and the Radio Relay Hardware (RRH) receivers were repowered for the first lime since December 1990 to support the firs[-ever inflight Probe Mission Sequence Test (MST) and an abbreviated System Functional Test (SFT). All power hardware functioned properly.

In addition to normal power control functions and activities, a series of commands were executed from [Ire stored sequence in April 1993 to close the contacts (if inadvertently opened during the launch phase) on several spare unused power switching relays to reduce the possibility of internal electrostatic discharge (IESD) events in the Jovian environment due to "floating" ungrounded wires.

In tile. past year only one pyro event was planned and that was completed perfectly. On March 4, the Energetic Particle Detector (EPD) instrument protective sun shade was retracted 10 provide a full clear EPD field-of-vic,w for Jupiter operations. This event was the last planned pyro event prior to Probe release scheduled for July 1995.

The oniy power anomalies observed arc those associated with the on-going AC/DC bus imbalance caused by slip-ring brush debris. All the observed bus imbalance changes arc benign, understood, and do not pose a threat to the spacecraft (Reference 4).

4.4 Command and Data Subsystem

The Command and Data Subsystem (CDS) and the tape recorder (DMS) arc in excellent health and continue to operate flawlessly. A CDS memory test was performed in late October 1992. The test activity read out the entire CDS memory. No memory parity errors were observe.(i, thus providing confidence that the 6504 RAM memory chips arc functioning properly. The CDS continues to process and execute all commands and stored sequences perfectly. Telemetry measurement collection, processing, and formatting functions are also operating perfectly. Many stored sequences containing from hundreds to several thousand commands have been executed including TCMS, Probe checkouts, HGA activities, Earth and Ida encounter activities, and special characterization tests/functions. Return of Ida data using the CDS and DMS to perform short-burst memory readouts worked perfectly during the planned early return of some Ida data in September 1993.

The CDS experienced five spurious transient bus-reset POR anomalies Ibis summer. After 692 days without such an anomaly, bus reset events recurred on June 10, June, 17, July 10, July 11, and August 11 11,1993. No CDS critical controller spurious transient telemetry POR indication has occurred since November 30, 1991. As designed, every bus-reset event resulted in onc side of the parallel operating CDS "going down," hailing of all stored sequence activity, and entry into safing. The cause of these anomalies is consistent with Spin Bearing Assembly (SBA) slip-ring brush debris forming unwanted circuit paths, coupled with simultaneous slip-ring brush lifts. See Section 7 herein and Reference 4.

4.5 Attitude and Articulation Control (AACS)

The. hardware and software elements responsible for all attitude control and pointing functions continue to perform excellently. See Section 6 for discussion of one ground-induced incident. There has been no evidence of failure or anomaly in any of the."1'CC-2.44 RAM memory chips. The AACS system superbly supported the Earth encounter activities and the Ida approach optical navigation and encounter imaging activities.

Five TCMs were flawlessly performed during the past year. In every case the AACS carried out the delta velocity maneuvers accurately and well within performance specifications. AACS also supported many HGA recovery action activities including HGA motor-/tower-warming turns and the HGA X-band RF-characterization tests. Several turns ranging from 20 to 45 degrees off-Sun were conducted; all were performed well within specification.

In mid-January 1993, two first-time activities were completed. A clock system (spacecraft scan platform azimuth control) identification was performed to determine flexible body structure modal characteristics. The structure was excited using five different SBA torque-motor pulse widths. Preliminary analysis indicates significant flexible body modes were identified. late.irlJanuary, the AACS was completely reloaded with the phase. 12.0 flight software. This software version enabled early verification of the 10.5 rpm spin up/down capability needed for Probe release and the 400-N engine firings in 1995 and 1996. Prior to loading the 12.0 software, memory tests were performed verifying that all the AACS TCC-244 memory chips are functional.

As part of the loading process, each 32 Kbyte half of AACS memory was separately tested and verified before loading the new software. Immediately after swapping to the A memory containing the new software, the scan platform unexpectedly slewed at a high rate and hit the zero degree cone. angle structural mechanical stop. Analysis revealed that the anomaly was duc to a software liming flaw that existed before launch and was not a result of the. 1'2.0 software. The anomaly can occur only after a memory swap and when a unique data sampling timing condition exists. A software patch was loaded shortly thereafter to preclude a recurrence of this anomaly,

In March 1993, while 1200 bps engineering telemetry was still available, the. first-ever 10.5 rpm high-rate spin up/down flight capability was demonstrated with the new software. The spacecraft achieved the high spin rate without incident and was kept at high spin for about 48 hrs bc.fore spinning down and returning to the dual-spin mode. Analysis indicates wobble was about 2 mrad higher than expected; the cause. is being investigated. Other dynamic signatures were as expected.

A scan platform overtravel test was performed in late May 1993 to demonstrate that the platform can be safely slewed throughout the. 180-1021 0-degree cone-angle region. Scan actuator friction characterization data was collected during this test. Preliminary analysis indicates no anomalies and the scan actuator friction levels are consistent with pre-test expectations.

4.6 Propulsion

The propulsion subsystem, which was built by MBB (now DASA) and provide.d by the Federal Republic of Germany, is healthy and has superbly performed all attitude change and maintenance, velocity change mane.uvers (TCMs), warming activity turns, and the high-rate spin up/down activities. All propulsion-related activities are performed via on-board stored sequences prepared by the Flight Team. To date, there has been no spacecraft closed-loop control of delta velocity magnitude. All TCMs were performed normally with execution errors of less than 1.5 percent.

The 10.5 rpm spin up/down activity was performed using the S-thruster 1.3-sec on/3.9-see off duty cycle for the. first time. It took 312 thruster pulses for the spacecraft to go from all-spin at 2.89 rpm to 10.5 rpm; the spin down required 313 pulses. Both values were near the predicted number needed at the existing RPM tank pressures.

During the 10.5 rpm spin down activity the S1 A thruster (S/N17) experienced a minor thermal anomaly. Review of ground test data for that thruster and other flight thrusters showed similar thermal behavior even after fewer pulse firings, albeit at somewhat higher pressure conditions. The observed thermal response was concluded to be a normal operating signature and poses no threat.

All pressures and temperatures have remained within acceptable limits and of the total usable propellant load of 925 kg, about 165 kg have been used to date.

4.7 Thermal Control/Devices

All spacecraft temperature requirements are being met, aside. from several hardware. temperature limit violations specifically waive.d by the Project in support of HGA recovery actions and the expected MAG inboard sensor temperature cold-limit violation for solar distances beyond 2.2 AU, Mainlining proper thermal control during the past year was a challenging task. The spacecraft trajectory went from about 1.4 solar AU (inbound to Earth) to about 0.98 ALI (post-Earth flyby perihelion) and out to about 3 AU at the Ida encounter. The spacecraft altitude, extremes varied from near Sun-point at 3 AU to 45 degrees off-Sun at 1 AU. in addition to significant variations in solar heat input, numerous sequence-planned electrical load reconfigurations were. thermally accommodated. "1'0 take full advantage of the solar conditions at 1 AU for HGA tower/motor heating, two off-Sun thermal characterization tests were conducted on the Ear (I I-2 inbound trajectory to collect needed information for setting the spacecraft thermal state at 1 All. As a result of the thermal tests, several electrical load states were modified, providing high confidence that the planned near-lkulll HGA activities could bc. done, safely. The spacecraft thermal response during the 45-degree off-Sun activity at 1AU was care.fully monitored to assure that all hardware remained within safe thermal limits.

Two mechanical dc.vice activities were completed this year: the EPD sunshade-retraction pyro event and the RRA slew-characterization test. Both activities were performed perfectly and within predicted values. Detailed analysis of the RRA slew data was recently completed and confirmed preliminary results indicating all RRA control and monitor hardware arc. functioning properly.

4.8 Probe Checkouts

On the Earth-2 inbound trajectory in mid-November and earl y December 1992, two Probe checkout activities were performed to take advantage of the high data rate near Earth (28.8 kbps). The first-ever inflight Mission Sequence Test (MS-I') was conducted on November 20, This test thoroughly tested all the }'robe scientific instruments and the actual Pi obc mission sequence. Subsequently, on December 2, the newly generated Probe Abbreviated System Functional Test (ASFT) was performed, The, ASFT is a significantly scaled-dowl] version of the System Functional Test for use with the LGA 10-bps data rate to check Probe battery voltages and expel argon gas from the Neutral Mass Spectrometer (NMS) instrument bc.fore. Probe Release. Data anal ysis by NASA/Ames, Hughes Aircraft Corporation, and Probe science personnel concluded that the Probe and all its instruments arc healthy and func tioned properly.

4.9 Orbiter Science

All the Orbiter science instruments are healthy and functioned excellently during Earth-2 and Ida encounter. Only one. instrument, the ultraviolet spectrometer (UVS) has shown any indication of a possible problem. During the Earth-2 approach after UVS power turn-on, telemetry indicated the instrument was not configured 10 the expected state. Subsequent investigation by the principal investigator's team concluded that the improper state was likely the result of a TCC-244 memory single bit flip caused by a transient read-disturb error. After the UVS was reset, the instrument operated flawlessly.

5. Propellant Margin

A Wailed summary of Galileo propellant expenditure both completed and planned was provided in Reference 3. The continuing excellent navigation and spacecraft per formance, especially al Earth-2, have. saved about 5 kg of propellant with respect to the past year's budget. A new statistical maneuver strategy for the maneuvers a few days before and after the JOI, particularl y adding an energy - correcting mane. uvc.r one. day after JOI, reduced the Jupiter phase statistical propellant requirement by 25 kg. } lowever, the reduction in navigation data available over the 1 ow-Gain Antenna during the satellite tour increased the Jupiter phase stati stical requirement by 20 kg. These changes and several small miscellaneous changes resulted in a propellant margin increase of 8 kg over this past year from -3 kg to +5 kg. By definition, Galileo l'lope.liant Margin (I'M) is tile usable propellant remaining after completing the baseline Jupiter Satell ite Orbital Tour of ten targeted satellite encounters al 90 percent probability. Thirteen kg arc allocated for spacecraft turns to point the instruments beyond the scan platform limits occasionally. Project Manager Reserves also total 13 kg. Therefore, potentially 31 kg of PM is available for contingencies - well over half the Jupiter-phase statistical requirement. The statistical requirement is the ***a priori*** uncertain component and by definition excludes al i deterministic require.rncrm such as the JOI AV.

6. Mission Operations - Selected Topics

During the past year the Flight Team designed and executed five Trajectory Correction Maneuvers (TCMs) (Fig. 4), imparting to the spacecraft a total of 4.3 m/s change in velocit y. Since launch a total of 197 "rajccW_y Correction Maneuvers (TCMs) have. been executed with more than 92.2 m/s in change in velocity. The second gravity-assist flyby at Earth imparted 7.7 ire/s change in velocity, producing the heliocentric velocity - 39 km/s nearly tangential to Earth's orbit - required 10 reach J upiter. The flyby was so accurate that the Flight Team did not have to execute TCM-18, which was nominally planned 10 occur 13 days after the Earth-2 flyby. The planned Earth-2 flyby altitude was 303.8 km; actual was 303.1 km. Comprehensive discussions of the actual navigation of the VEEGA trajectory are given in References 5 and 6.

A most significant challenge to the Flight Team this year was the development, test, and uplink of new Attitude and Articulation Control Subsystem (AACS) flight software. This version of the flight software (Version 12.0) constituted a complete reload of the flight software - the first ever for a planetary spacecraft. The AACS 12.0 flight software included lilt. capability 10 execute the 10.5 rpm spin up/down using the 10N thrusters in the required pulse

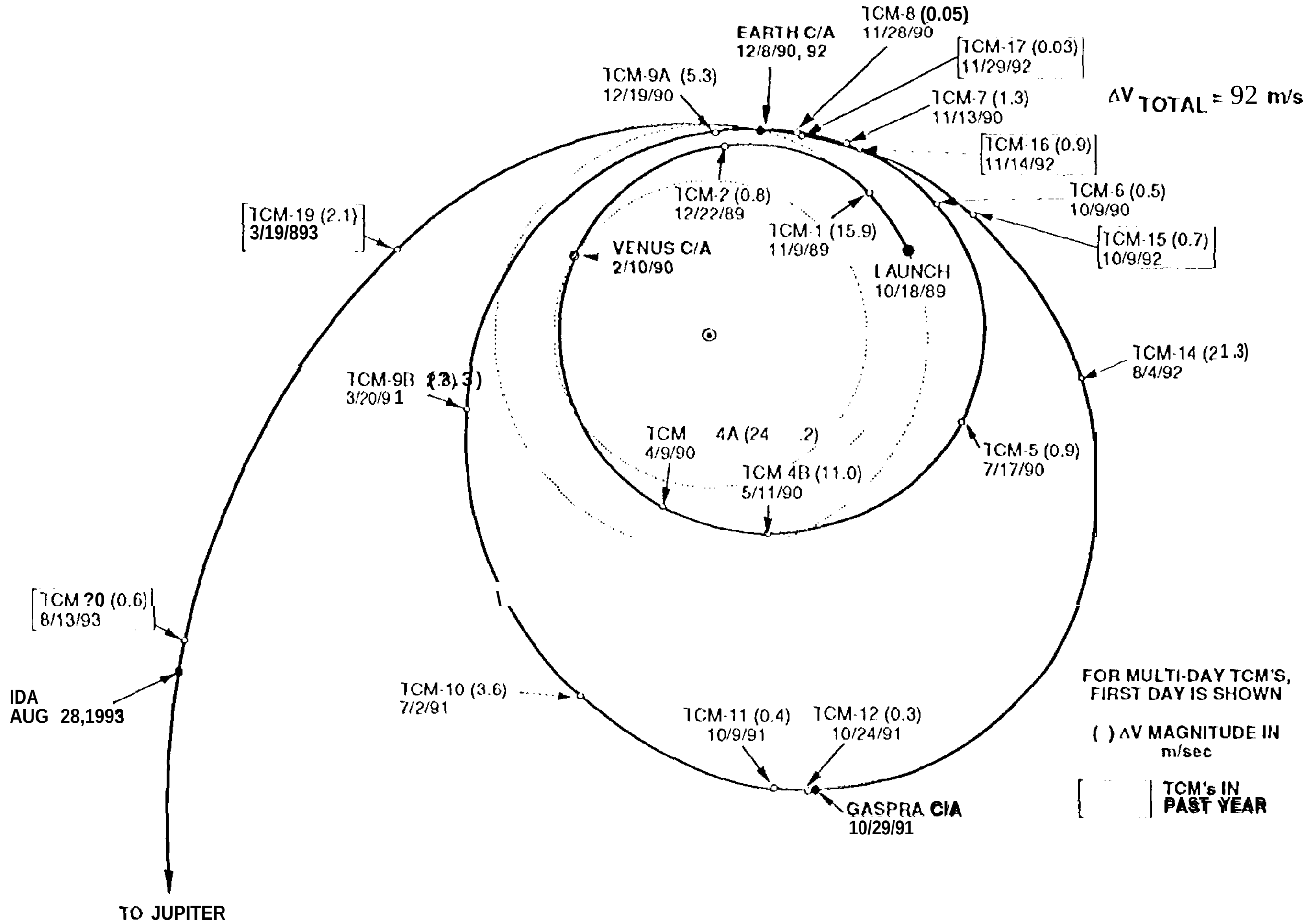


Figure 4. Trajectory Correction Maneuvers to Date

mode operation. In addition, new code correcting ten Flight Software Problems (FSP's) discovered inflight was included in the design.

The in flight load process was extraordinaril y complex, requiring an address by address verification of the functionality of the AACS flight memor'its, the uplink of the flight software to the primary of the two redundant memories, switching operation 10 the new flight software, and then finally loading the other memory. This entire process took approximately 96 hrs of continuous operations with a 24-hr planned pause to allow for schedule recovery had there. been problems with the spacecraft or tracking stations that would have affected the time.fil~c.

Prior to being accepted for upl ink 10 the spacecraft, the AACS 12.() flight software was carefully and thoroughly tested using the Galileo Test Bed, a hardware and software replica of the essential flight spacecraft subsystems. The subsystem test program started in May 199?. and was completed in August. Following subsystem testing, a system-level test program was undertaken spanning the period August through mid-October. In addition, the inflight load sequence was tested at both the subsystem and system level. This flight software test program was judged to be even nmrc thorough than the prelaunch test program,

The inflight load started on January 25, 1993, and was accomplished as planned except for one anomaly which occurred on J anuary 28 when the AACS memory was swapped and AACS started executing the 12.0 flight software. The In-Flight 1 oad (1 FL) process was suspended tempor aril y pending anomaly resolution. The process was resumed on January 29 and completed the following day. The anomaly, which had been present in the old prelaunch version of the flight software, involve.(f the improper setting of a crucial variable used to control the scan platform (see 4.5 Spacecraft Perfor mance/AACS). The IFL activity was operationally very complex and in spite of the anomaly was executed successfully. The anomaly was quickly detected and understood; permanent patches to the AACS 12.0 flight software were uplinked 10 the spacecraft within three weeks.

The Galileo Space.cr-aft was dc.signed to be controlled by onboard computer programs called sequences. Very little "rc.al-time" commanding was envisioned in the design of the Ground Software or in the sizing of the Flight Team.

The 1 ligh-Gain Antenna recovery efforts dramatically inci cased the number of real-lime. commands sent to the spacecraft. As of August 1, 1993, 130,890 commands had been transmitted 10 the spat.ccraf[; nearly 72,(JOO were real-time commands, and of that number nearly 60,000 were asso ciated with the dual drive actuator "motor hammering" undertaken this year as the Project continued its efforts to release the stuck ribs of the High-Gai n Antenna. Of the 130,890 commands transmitted since launch nearly four years ago, a total of 64 ,800 or 50 percent were sent this past year. In one sense this number is misleading because many of the commands were cyclic (i.e., repeated use of the same. set of commands) and were transmitted over a compara-live.ly siloIll)cri(J(ioflirllc. On the other hand, this effort occurred shortly after the Earth-2 encounter and prior m the IFL of the AACS 12.0 flight software. The four-month period from m id-November through mid-March was the most operationally intense and demanding interval of the mission so far.

7. The Perils of Ida Encounter

On J June 10, 1993, a Command and Data Subsystem (CDS) A-String b us reset spacecraft safing occurred. This was immediately recognized as the same phenomei ion that occurred three times in 1991: once on B-String, twice on A-String. A specific shorting configuration in the Spin Bearing Assembly (SBA) produced by aggregated slip-ring brush wear debris in conjunction with brief (10 µsec) simultaneous lifting of the brush pair on a re-set signal ring cause.sa spurious reset. The CDS hardware response on the string with the reset signal is to halt and send an alert to the other string. In the CDS software response, the other string safe.s the spacecraft, stops the onboard programmed sequence, and waits for ground commands. This protects the spacecraft from an errant CDS. The debris shorts are sel - limiting in that they burn open before. current level is hazardous to any electronics. So this reset phenom enon is benign except that it halts the spacecraft sequence. The Flight T 'cam must prepare and uplink substantial command packages 10 bring up the. down string and they must generate and uplink a revise.d spacecraft sequence to resume operations. Incidental ly, this is not a threat to Probe Relay and JOI because the Relay/JOI flight sequence is programmed to continue execution even if one string goes down.

A second reset occurred on June 17. This pair of resets was viewed as random and since the frequency of occurrence was greatly diminished as expected due to wear-in - none had occurred in nearly two years - resets were not considered a particular threat to (he, upcoming August 28, 1993 Ida encounter. This situation changed abruptly in July when resets occurred on July 10 and 12. The first of these precluded capturing the first of five planned Ida optical navigation images. Clearly, contingency plans were now necessary to cope with CDS bus resets. In all-spin mode there is no motion between brushes and rings so brush lifts do not occur and, therefore, the spuriou s resets do not occur. It was decided to keep the spacecraft in ail-spin mode except when it had to be dual-spin for observations or for maneuvers. There was no evidence that the transitions from ail-spin to dual-spin in themselves contributed to resets; minimizing time in dual-spin regardless of the number of transitions seemed most prudent. Then on August 11, during transition to dual-spin for the third navigation image, a reset occurred precluding the image. The 1 'light Team quickly recovered the CDS, uplinked a prerequisite attitude change, and executed TCM-20 on schedule on August 13, 15 days prior to the Ida encounter.

The Ida encounter plan was to stay all-spin until -12, hrs when dual-spin was required for a spacecraft attitude maneuver to improve. the observation geometry. The reset recovery process was being aggressively streamlined so that recovery could be completed in 32 hrs. 1 lowever, the. August 11 transition rc.set argued that transitions should not be performed beyond the point of no recovery. Accordingly, the final transition 10 dual-spin was performed at Icta-52. hrs, allowing settling time during which the final appi oach maneuver (TCM-21) could be performed with still ample time to rc.c.over from a reset. Virtually the entire encounter sequence could stil I be performed if the reset occurred as late as Ida-44 hrs. Ultimately, the recovery process was stream lined down to 15 hrs and an abbreviated contingenc y encounter sequence was designed and pre-generated that would start at Ida-6 hrs, thus reducing the period of no recovery to the 21 hrs bc.fore Ida closest approach. Happily, there. were no bus resets after August 11. Three of the five planned optical navigation images (#I?, #4, #5) were obtained. The first image (#2) was the. basis for the Ida-15 day TCM-20 and it was so good that the Ida-2 day T 'CM-21 and all scan platform pointing contingency update.s were canceled at Ida-5 days, when the final navigation estimate incorporating image.s #4 and #5 showed that TCM-20 had hit the bullseye. Galileo was just 0.7 sec early and 10 km high -- encounter would be at 16:51 :59,0 UTC at 2.410 km from Ida without performing TCM-21.

The events leading to Ida arc illustrated in Fig. 5. Note that rc.vised sequences (EJ -2', 2") had to be generated and uplinked to do the navigation following the July and August CDS bus resets.

Because Galileo's HGA did not deploy properly all communication must be over the i .GA; the resulting 1 0^4 weaker downlink signal can only be received by the. large 70-m antenna at each DSN com plex. When communicant ion with the Mars Observer (MO) spacecraft was lost on August 21, almost all of Galileo's 70-m tracking was reassigned to MO to provide maximum receive capability 10 MO. ironically, al this time Galileo and MO were only ten degrees apart as viewed from Earth. "1'bus, Galileo could be tracked only several hours a day for the next five days during the station viewing overlap (e.g., when both spacecraft were. setting at Goldstone, California and rising at Canberra, Australia). Navigation Image #/5 was shuttered the morning of August 21 and oniy one-fourth of it had been returned to Earth when the 70-rn stations were re-assigned

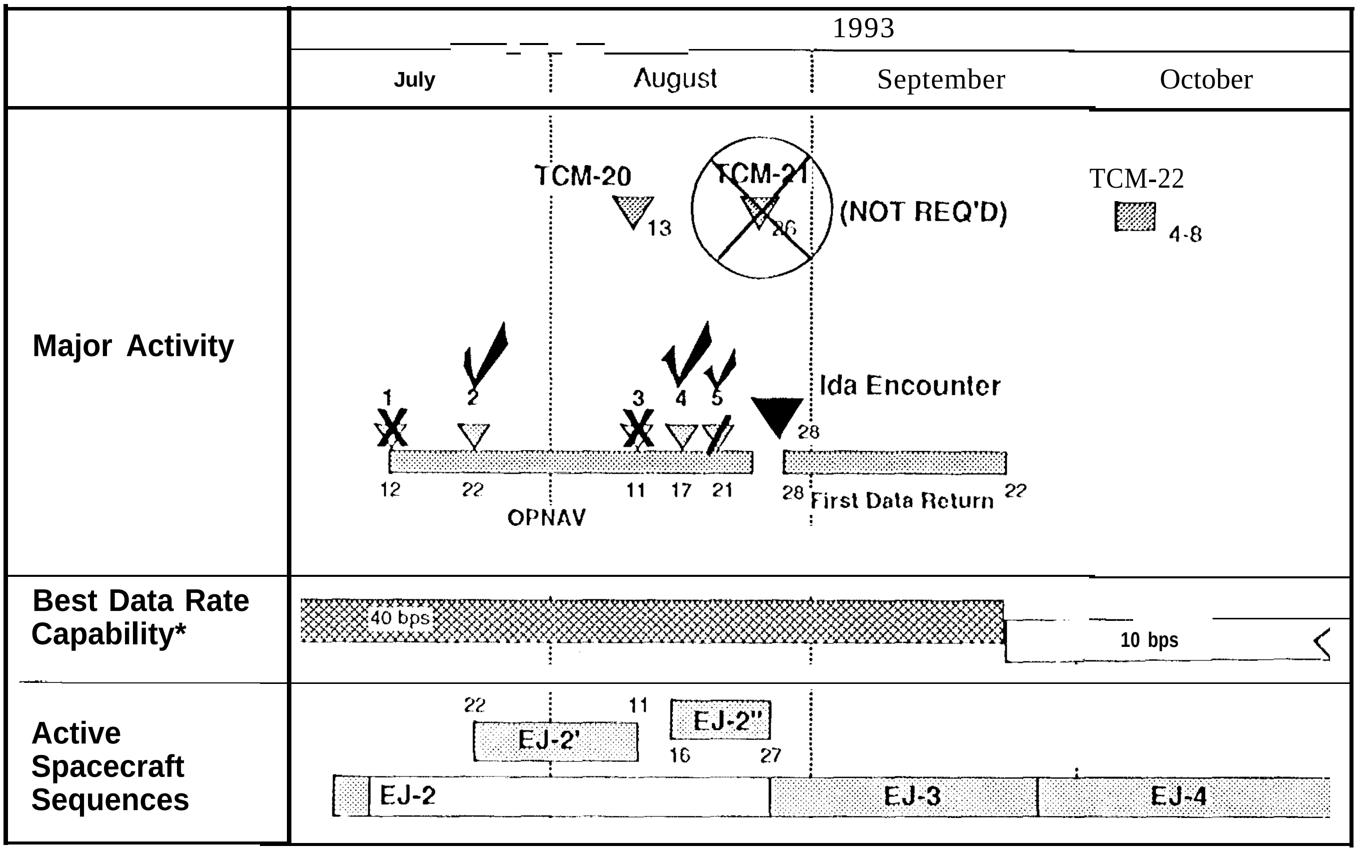


Figure 5. Events Leading to the Ida Encounter

that evening. Fortunately, five excellent data points were available.in the partial image.

Effective with the transition to dual-spin at Ida-52 hrs, the DSN 70-m priority was returned to Galileo. Everything was then set for the encounter. However, the 21-hr period before closest approach was onc of great anxiety since a random bus reset would have irrevocably killed the observation sequence.

While the dreaded reset did not occur, a significant but manageable incident did. At Ida-4 hr 16 min, the spacecraft autonomously turned off its gyros and switched to "cruise - mode" wherein the scan platform pointing would be controlled only by the loops "around" the actuator encoders with the spinning section providing the sole attitude reference "platform." The attitud e control engineers quickly confirmed the pointing would be only mode.s[ly degraded and that the encounter would execute properly in the "cruise-mode." However, a precisely timed ground command was required to be sent at Ida-3 hr 18 min to arrive at the spacec raft 30 minutes later (the one-way light time) to return the scan platform to the nominal pointing position for the next observation, as the platform had been autonomously moved to a slow position in the mode. transition - an intended fault response.

An excellent Ida encounter was performed with virtually all observations recorded; a few far-encounter images may have been missed due to the platform slowing.

A few days after encounter a special "jail bars" search technique was used to locate Ida in the mosaic by returning to Earth several adjacent lines out of about every 300 lines for every frame in the 30-frame high-resolution mosaic taken between -5.5 min and -1 min. The Ida image was found straddling frames 11, 12, 13, 14, and 21 (Fig. 6). The Data Memory S ystem Memory Read-Out (DMSMRO) technique was used to return the image (Fig. 7), just as it was for the Gaspra image in]991. About 150 lines of an image are copied from the tape (the DMS) into CDS memory and this memory is then transmitted 10 the ground (Memory Read Out). Nearly all of the 35 DMSMROs available before. the communication distance precluded 40 bps as of September 23 were required to return the five frames. Initially, only one small sequence of commands was required to perform the. various tape. recorder(IJMS) positioning slews to read the frames. However, on September 5 a totally unprecedented problem occurred: the main

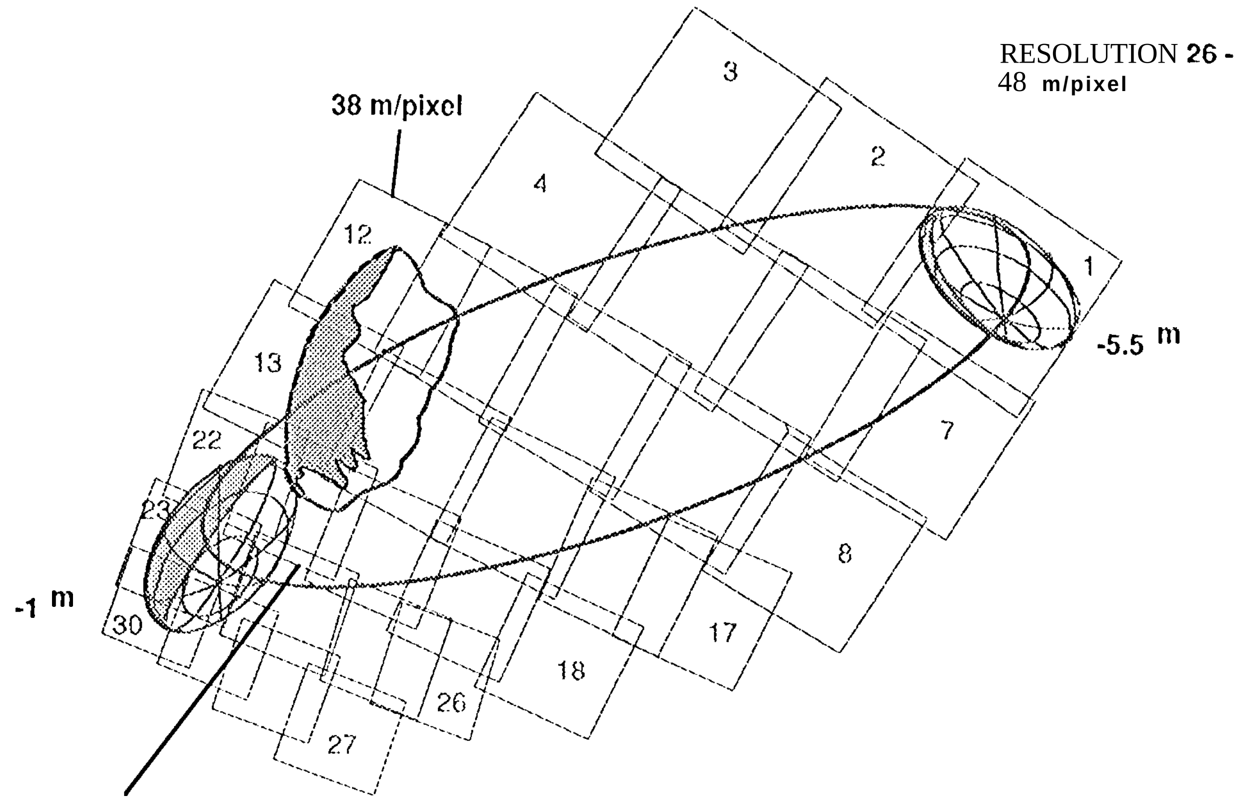


Figure 6. SSI/NIMS High-resolution Observation of Ida with 95% Confidence

Figure 7. Five-image mosaic of asteroid 243 Ida, taken at ranges from 3057 to 3821 km at relative velocity of 12.4 km/s. Ida is about 52. km long. Spatial resolution is 31 to 38 m/pixel.

transformer for the Canberra 70-m antenna shorted out and it took six days to get the antenna back oll-line. The Flight Team had to design and uplink five more small sequences to work around the Canberra outage, including replaying the image segments that were transmitted but could not be received during the Canberra outage.

The long-standing plan is to play back the rest of the Ida data when the Earth's orbital position next spring will bring it once again close enough 10 Galileo for 40 bps. (Note that, as dc.scribed elsewhere in ibis paper, DSN and spacecraft telecommunications improvements arc, now being implemented that wilt enable up to 160 bps at Jupiter.) Figures 8 and 9 summarize the Ida observation sequence.

A total of 150 Solid-State Imaging (SS1) imaging frames were recorded. Nearly half of these were required for the spatial mosiacs needed 10 cover the Ida position uncertainty. Ultimately, 13 color and 8 black and white images wil Ibe produced from [he. SS1 data. The Near Infrared Mapping Spectrometer (NIMS) also made extensive observations.

The Magnetometer instrument (MAG) data collection profile was enhanced performing several MAG MROs from encounter -12.5 hrs to + 6 hrs. Additionally, a newly devc.loped scheme for collecting MAG data at high sampling rate was used within ± 1 hour of closest approach; this high-rate MAG data was stored in the CDS.

All 1] Galileo Orbiter instruments made measurements at Ida, with the exception of the Heavy Ion Counter (HIC).

8. New Capabilities and Mission Description for Low-Gain Antenna

8.1 Mission Description

Performing the. Galileo mission with the 1 rev-Gain Antenna (1 .GA) was first described in Reference 3, and that description provides an introductory overview for the following implementation (discussion.

Because of the extent of the software changes required to perform the mission using the. LGA and the limited size of the on-board memories, the Galileo mission using the 1 .GA must be accomplished with three distinct software loads.

The existing spacecraft software, sometimes called Phase O, will be used until about March 1995. The software in the spacecraft Command and Data Subsystem (CDS) will then be modified, through in-flight patching, to provide a means of storing Probe data in CDS memory to backup the flight tape recorder storage. "Ibis Phase 1 software will be active on the space.craft from March 1995 through March 1996, during which time Probe data will be collected and returned 10 Earth. Jupiter Approach data, including 10 data

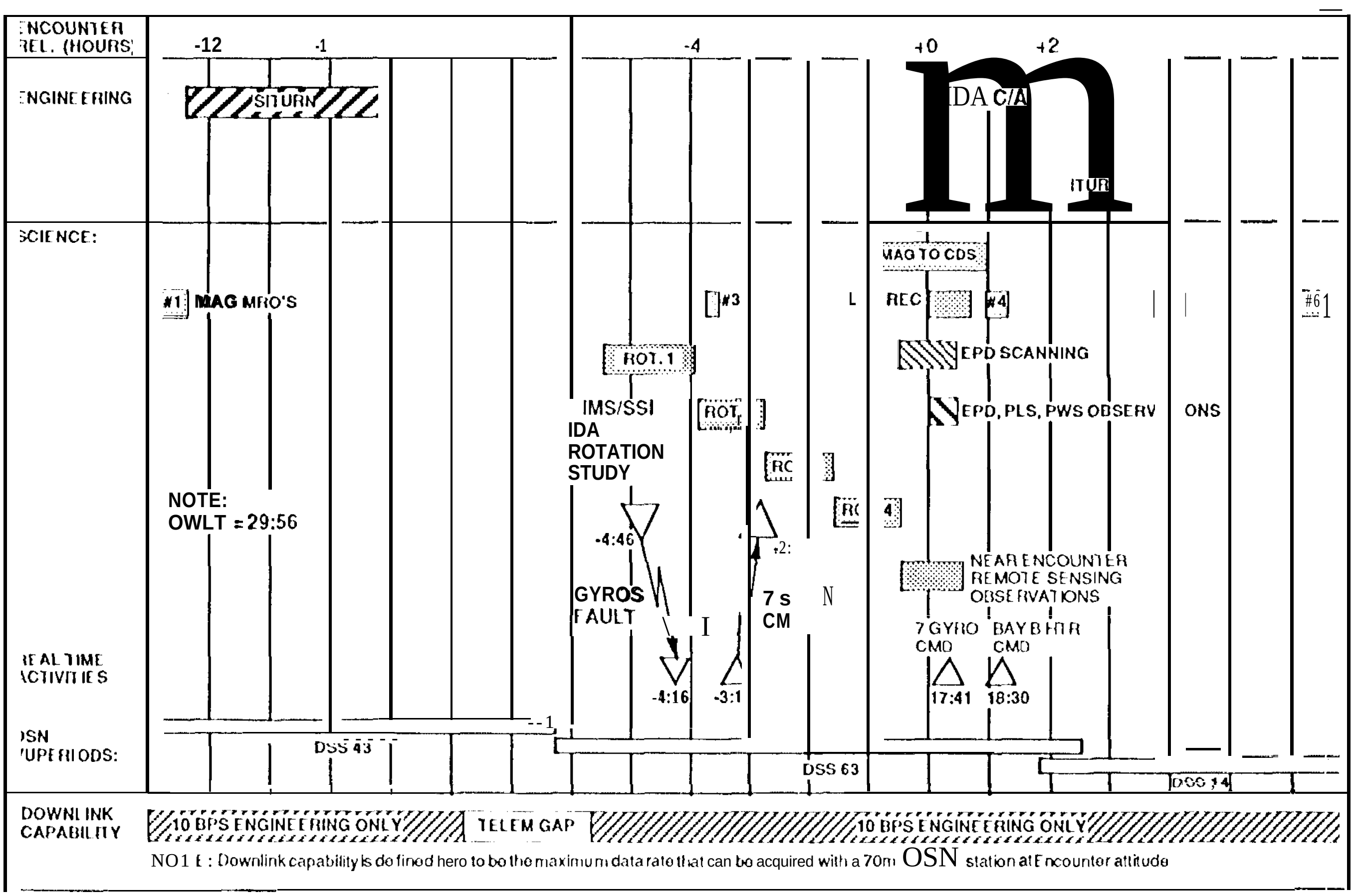


Figure 8. Ida Encounter Timeline Summary, -12 hrs to + 6 hrs

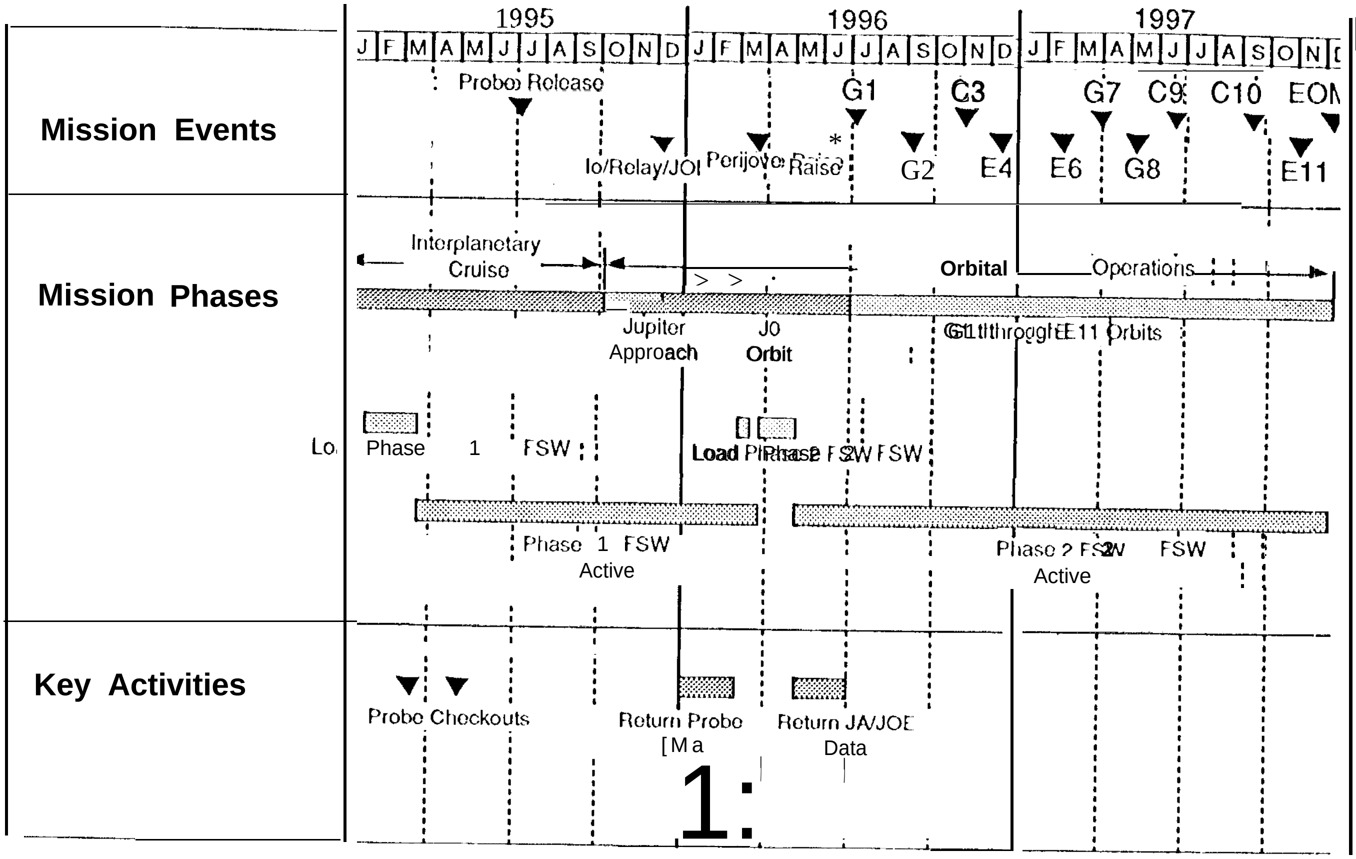


Figure 10. Mission Overview

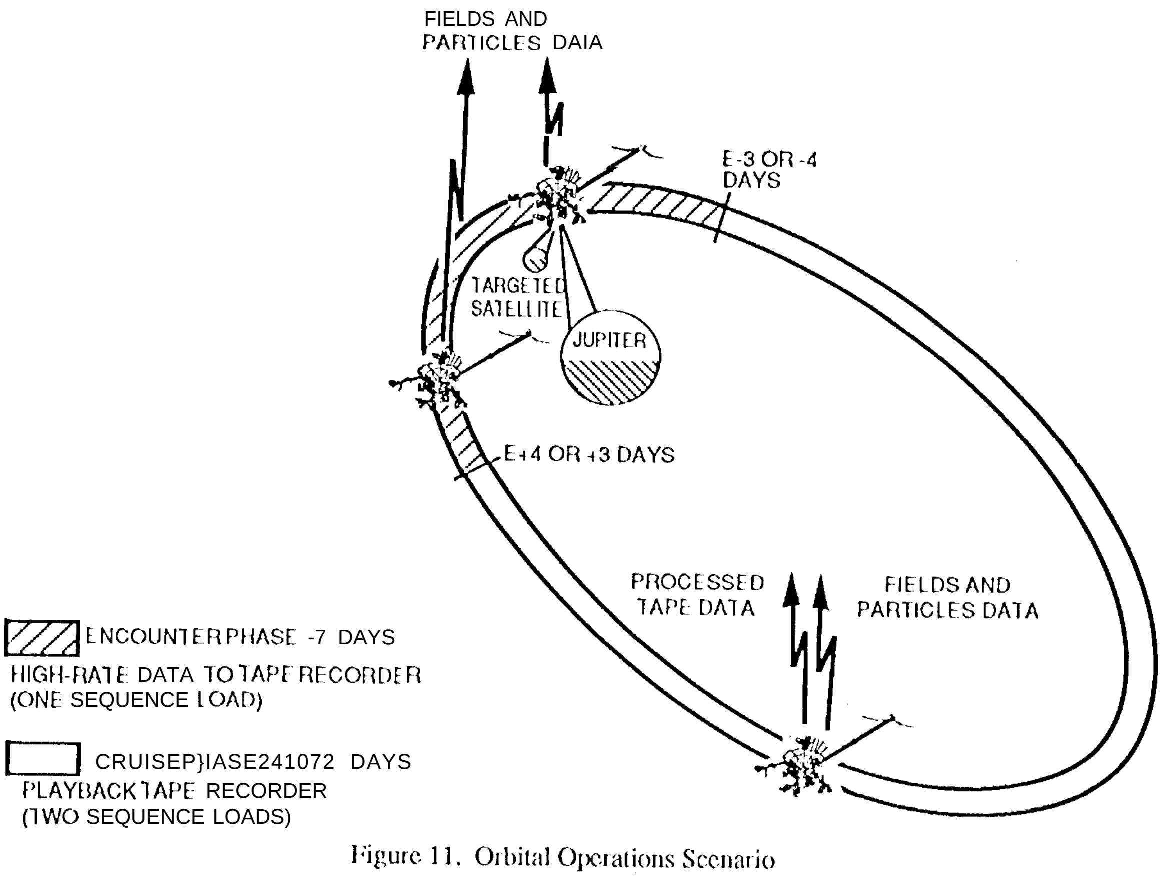


Figure 11. Orbital Operations Scenario

and JO] engineering data, will also be collected but not returned until the Orbital Operations phase of the mission.

Patches to the Attitude and Articulation Control Subsystem (AACS) software will be sent 10 the spacecraft al the same lime as the. Phase 1 CDS flight software (FSW). These changes support]'robe Relay and JOI.

Lastly, Phase 2 changes consist of a much larger software change, to the CDS, plus additional changes to the AACS and changes to most of the science instruments. Phase 2 change.s will be made in March 1996 and will remain active throughout the remainder of the mission, which consists of most of the Orbital Operations period and ends in December 1997.

1 'igure I () shows the major events that occur during the periods when the Phase. 1 and Phase 2 software are active. Probe Release occurs in July 1995 while still in Interplanetary Cruise, but with the Phase 1 software loaded. The encounter with 10, Probe Relay, and Jupiter Orbit Insertion (JO]) all occur on December 7, 1995. Probe data return immediately follows in January and February 1996.

The Phase 2 software is uploaded beginning in March 1996 after which time the Jupiter Approach (JA) and Jupiter Orbit Zero Encounter (JOE) data will be returned. This return will complete just in lime for the first Orbital Operations encounter with Ganymede in July 1996.

A total of ten J upiter satellite encounters will occur during the Orbital Operations portion of the mission. As shown in Fig. 11, each of these encounters will consist of an approximately 7-day encounter with Jupiter and the satellite, followed by orbital cruise during which the data collected during the encounter is returned 10 Earth. Fields and particles data will aiso be collected and returned in real-time during most of each orbit. Additionally, a fcw remote-sensing science observations may also be made and recorded during the orbital cruise period for later return during tile same orbit.

Each of the ten encounter orbits is of different duration and each occurs at different I lrrrli]-lo-spacecraft range (due to Earth's motion about the Sun), resulting in unequal amounts of data being returned from the ten orbits. Orbit, start date, days to return data (which dots not include the 7-day encounter itself), and spacecraft-to-Earth range in AU arc shown in Table 1.

Table 1. Galileo Orbit Playback Times and Earth-to-Spacecraft Distances

Orbit	Start Date	Data Return (days)	Average Spacecraft-to-Earth Range (AU)
G1	Jul 6, 1996	57	4.2
G2	Sep 8, 1996	55	4.7
C3	Nov lo, 1996	34	5.7
E4	Dec 21, 1996	40	6.1
E6	Feb 23, 1997	36	6.0
G7	Apr 7, 1997	26	5.5
G8	May 10, 1997	43	5.0
C9	Jun 29, 1997	77	4,3
C10	Sep 21, 1997	42	4.3
E11	Nov 9, 1997	28	5.0

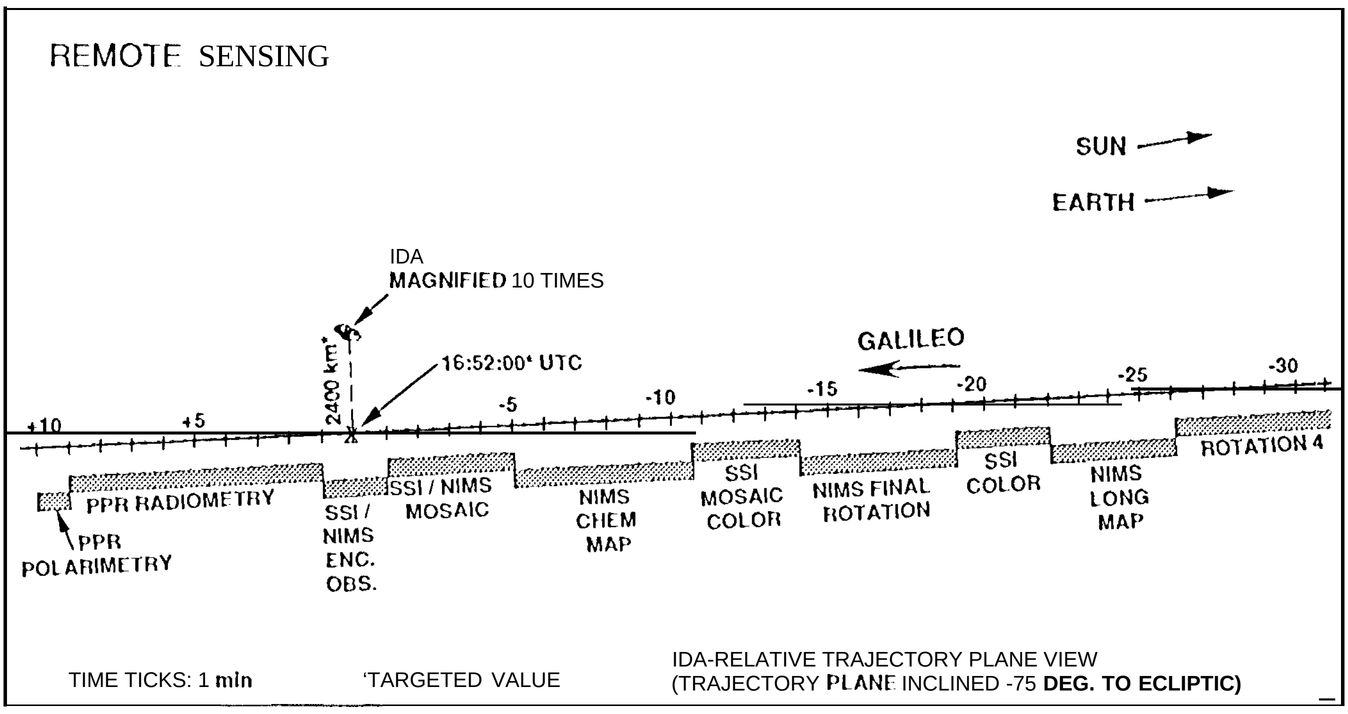


Figure 9. Rc.mote Sensing Observations from -30 min 10+ 10 min

8.2 Spacecraft Description

Reference 7 provides an overview Or the Galileo spacecraft and Reference 8 describes the CDS. Although a very brief description of parts of the spacecraft relevant to the modifications being made to support the LGA-based mission will be given here, more detailed information can be obtained from the references.

Figure 12 shows the Galileo space.crafl and the location Or some of the more. significant elements Or the spacecraft.

Figure 13 shows a simplified block diagram of the spacecraft showing the major subsystems. As can be seen in the figure, the CDS plays the central role in communicating and controlling, spat.ct.raft functions.

The Data Memory Subsystem (DMS) (Fig. 13) provides a single Odetics model DDS-3100 tape recorder with a capacity of 900 Mbits. Originally, this provided a backup means for obtaining Probe data in the event of interruption of the real-tinm downlink during Probe Relay or the link was unusable. duc to an SBA failure. With the failure of the. HGA, [he. DMS recorder becomes the primary means of returning Probe data. Because of this, software change.s arc. being made in Phase. 1 to provide the ability to store a reduced set of Probe symbols in CDS memory in order to re.store partial redundancy to the Probe data return path. This reduced set is sufficient to complete the primary scientific objectives of the Probe mission. Details of' these. changes arc provided later in this paper.

The key factor which enables all of the. changes for Phase 1 and Phase 2. is the availability of CDS extended memory. This memory, which is one half Or the total CDS memory (192 kbytes out of 384 kbytes, where 1 kbyte = 1024 byte.s), was added prior to Galileo's launch duc to a concern over the reliability of the 6504 memory devices for the 8-1/2-year VEEGA mission. These devices, however, have proven 10 be quilt reliable, without a single failure so far on either the Galileo spacecraft or the Magellan spacecraft (which uses a duplicate of the Galileo spun CDS). Since the CDS was designed to complete its original mission without the usc of any of the extended memory in either siring, the reliable performance allows the usc of this extended memory in both strings to perform the mission with the LGA without impacting existing spacecraft capabilities.

This memory is not accessible by any single CDS processor, but is instead distributed in the memory space, of the six 1802 processors or is available. as a memory device on the CDS data bus. Figure 14 shows how the processors and memory are distributed in onc of the two (identical) CDS strings. The memory numbers shown include both original and extended memory. The High-Level Module (HLM) shown in the figure controls all bus transactions and [bus controls movement of all data and commands between memories and processors.

Both of the Phase 1 and 2 designs utilize all of this available. memory, which makes the new code non-redundant and mans that loss of part of the CDS memory could cause loss of some Probe symbol data in Phase I and could require reduction of capability in the Phase 2 design. All engineering functions remain redundant as in the original design.

8.3 Phase 1

The major objectives for the Phase 1 development arc: to protect Probe data against DMS problems, make efficient usc of the downlink channel to return probe data, provide. robustness to CDS anomalies, and increase PWS data content in orbiter science data recorded during 10 torus fly-through. A secondary objective is to allow all change.s to be patched into the running CDS; i.e., avoid having to bring a CDS string down during the software loading process.

Figures 15 and 16 show a very-high-level summary of the capabilities being added to the spacecraft and ground system in support of these objectives. The remainder of this section describes these capabilities in more detail.

8.3.1. Data Capture

To restore. Probe data redundancy in the. LGA-based mission, a partial copy of Probe symbol data will be stored in the extended CDS memory. Due to the limited amount of this memory, only a portion of the Probe data received from the Radio Relay Hardware (RRH) can be stored.

The structure of the Probe data stream, as received by the. RRH is shown in Fig. 17, The Probe. data comes into the CDS from the RRH in blocks of 54 bytes, consisting of 27 bytes from each of two RRH channels, designated A and B. Each group of 27 bytes consists of a sync byte, 8 bytes of RRH data (the 12th bit of which indicates RRH receiver lock status), and 18 bytes of Probe data. Each of the first 16 bytes of Pmbc data consists of 2 Probe symbols (1 bit each) which the RRH expands to 3 bits each with signal quality data, plus 1 zero bit per symbol. The 17th byte and the first nibble (4 bits) of the 18th byte. have either a zero followed by one expanded Probe symbol or arc all 1's (each nibble considered separately). The last nibble in the. 18th byte is always all 1 's.

Only the individual Probe symbol bits arc stored in CDS memory. For the first 16 bytes of Probe. data, the CDS strips out the two Probe symbols per byte. For the 17th and 18th bytes, the logic looks at the first bit in each of the first three nibbles and either strips out the Probe symbol bit or ignores the nibble. The last nibble of the 18[1] byte is ignored. Thus, for each 81 bytes of Probe data received from the }{1<11, only 13 bytes Or stripped symbol data arc stored in CDS.

in total, the.rc. is sufficient CDS memory 10smrc31.3 minutes of data from both 1<1<11 channels (stored in HLM extended memory), an additional 8.S minutes of data from one. (selectable) of the two RRH channels, (store.(i in the. spun Buffer Memory, or BUM, extended memory), and 75 minutes of c.very other Doppler wind data measurement from RRH-A (stored in the DMS Buffer Memory, or

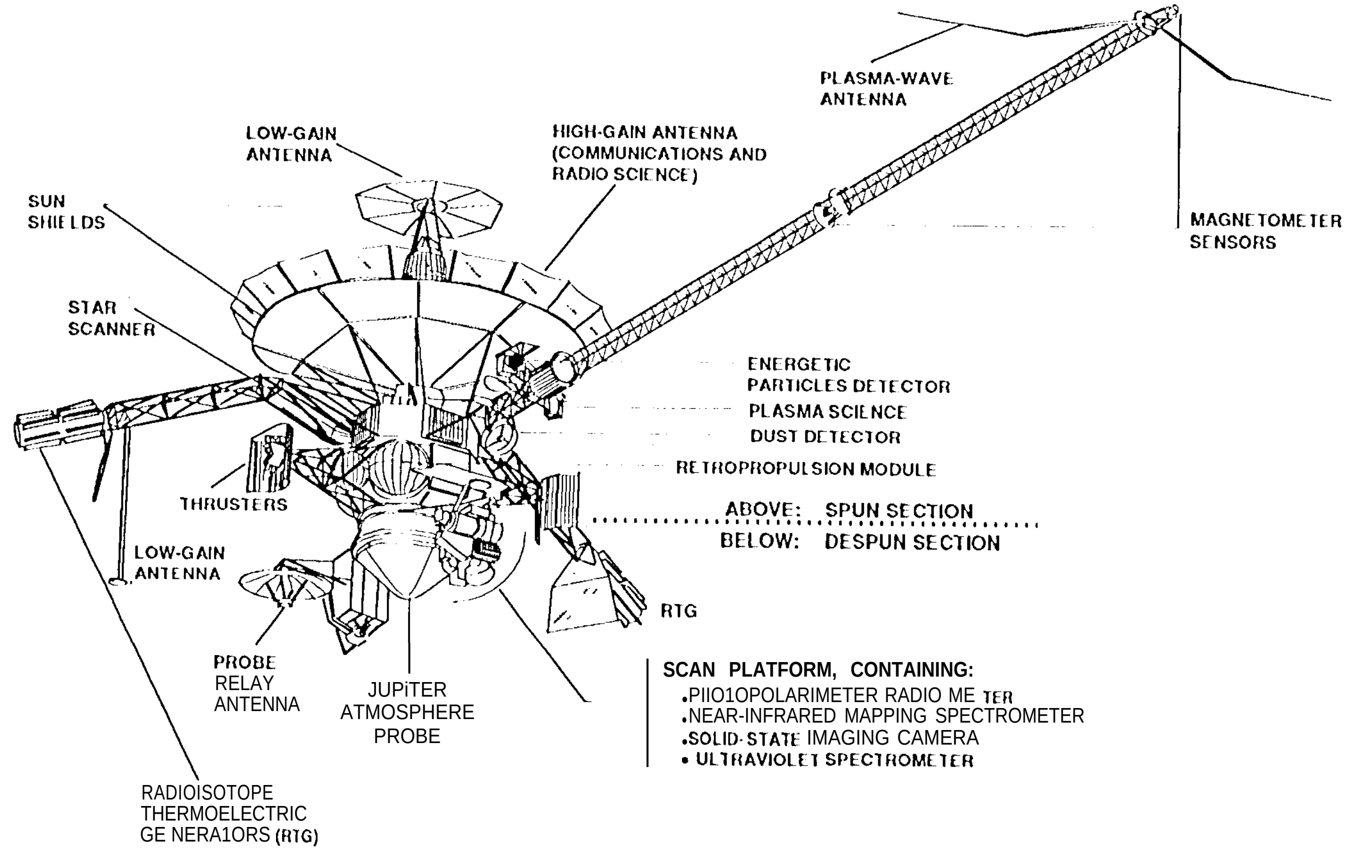


Figure 12. Galileo Spacecraft

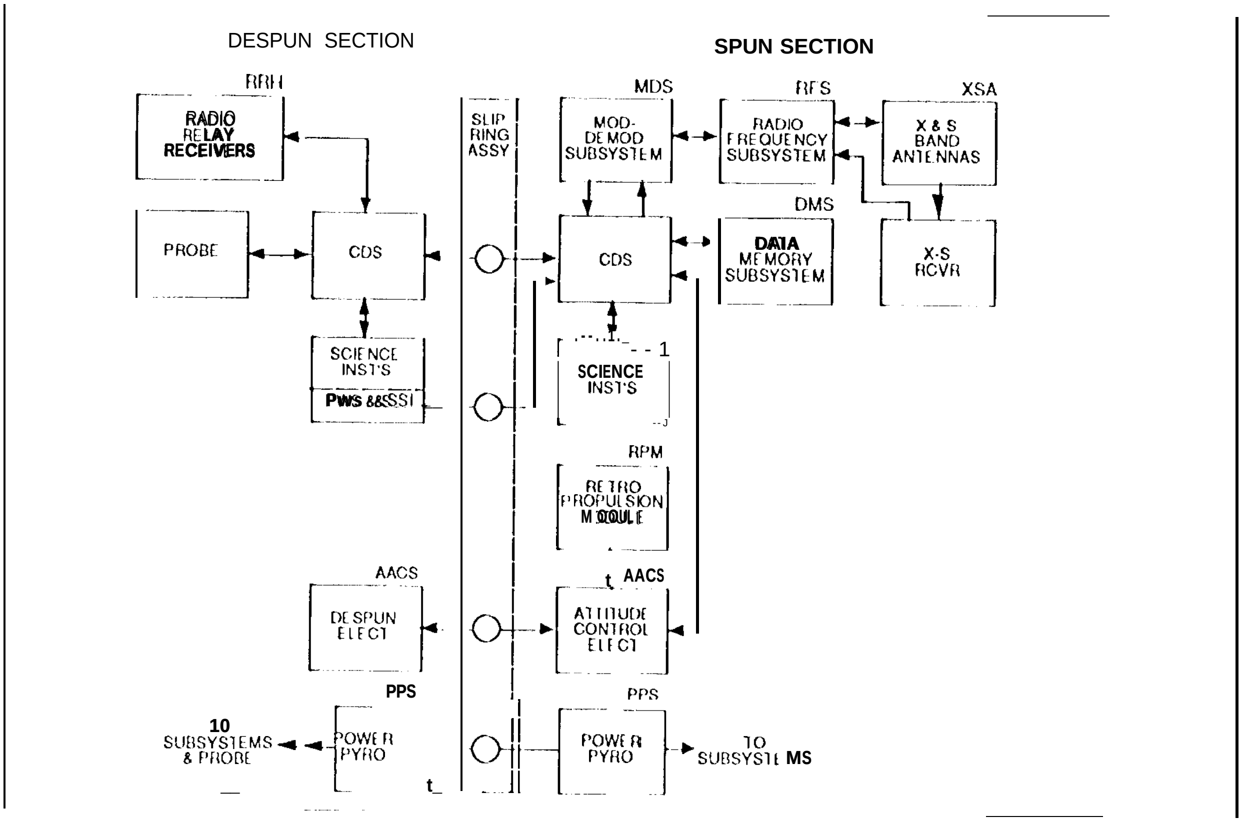


Figure 13. Orbiter Simplified Block Diagram

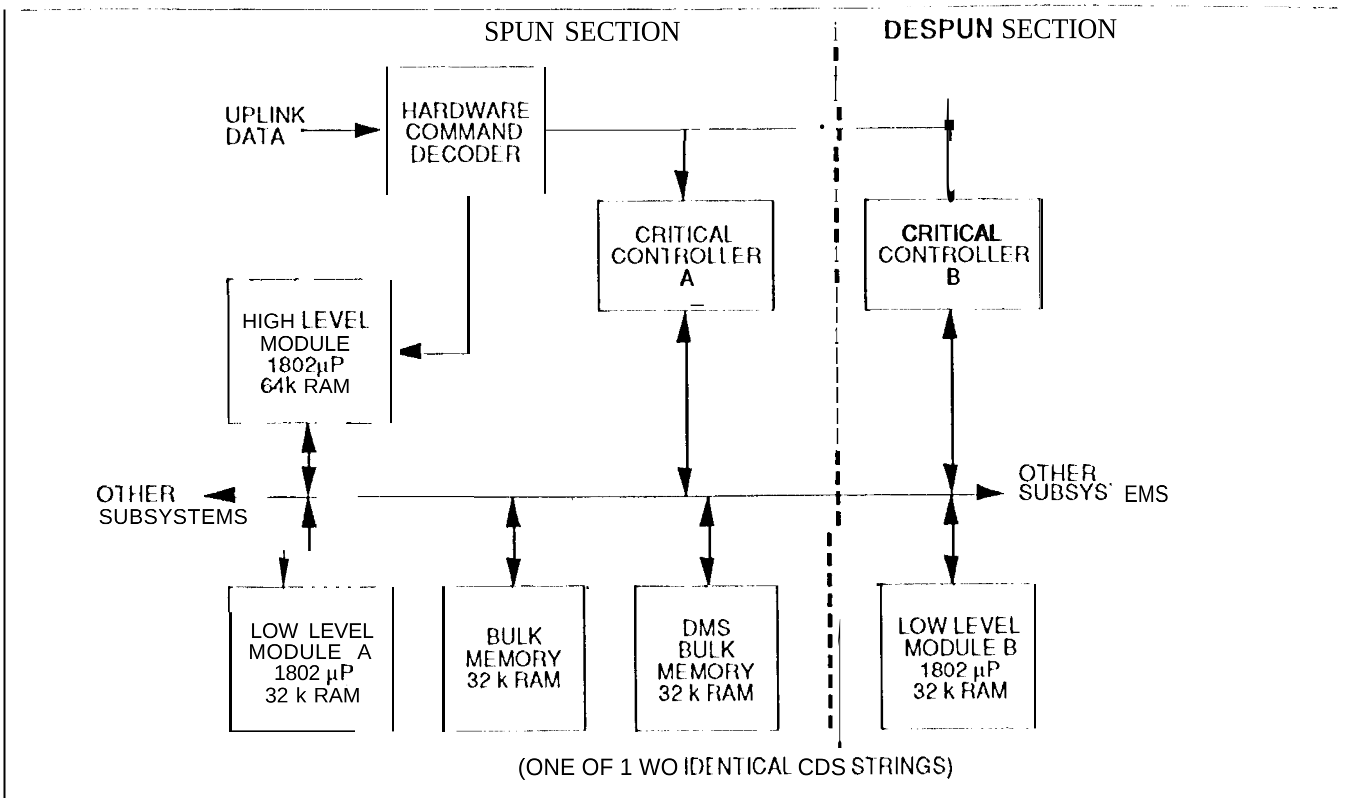


Figure 14. CDS Memory Configuration

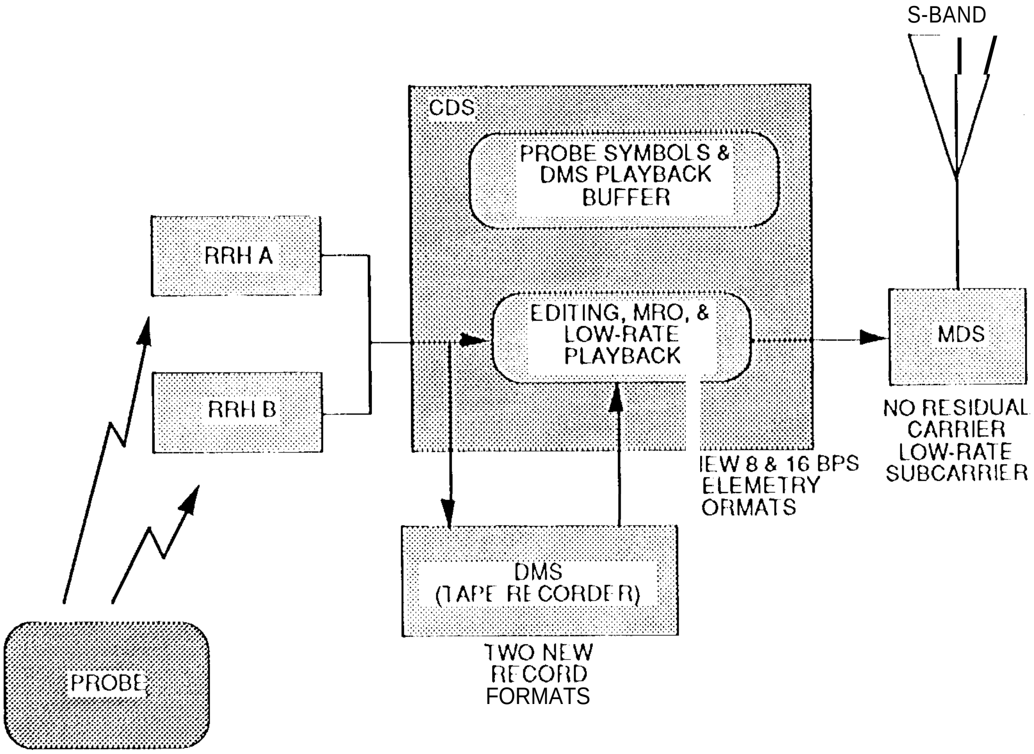


Figure 15. Phase 1 Spacecraft Design Overview

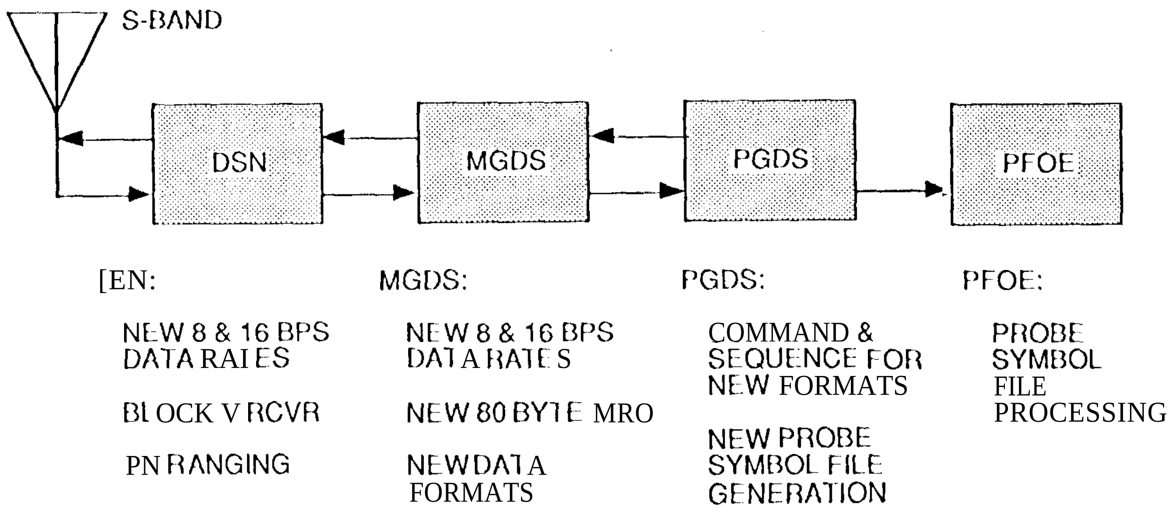


Figure 16. Phase 1 Ground System

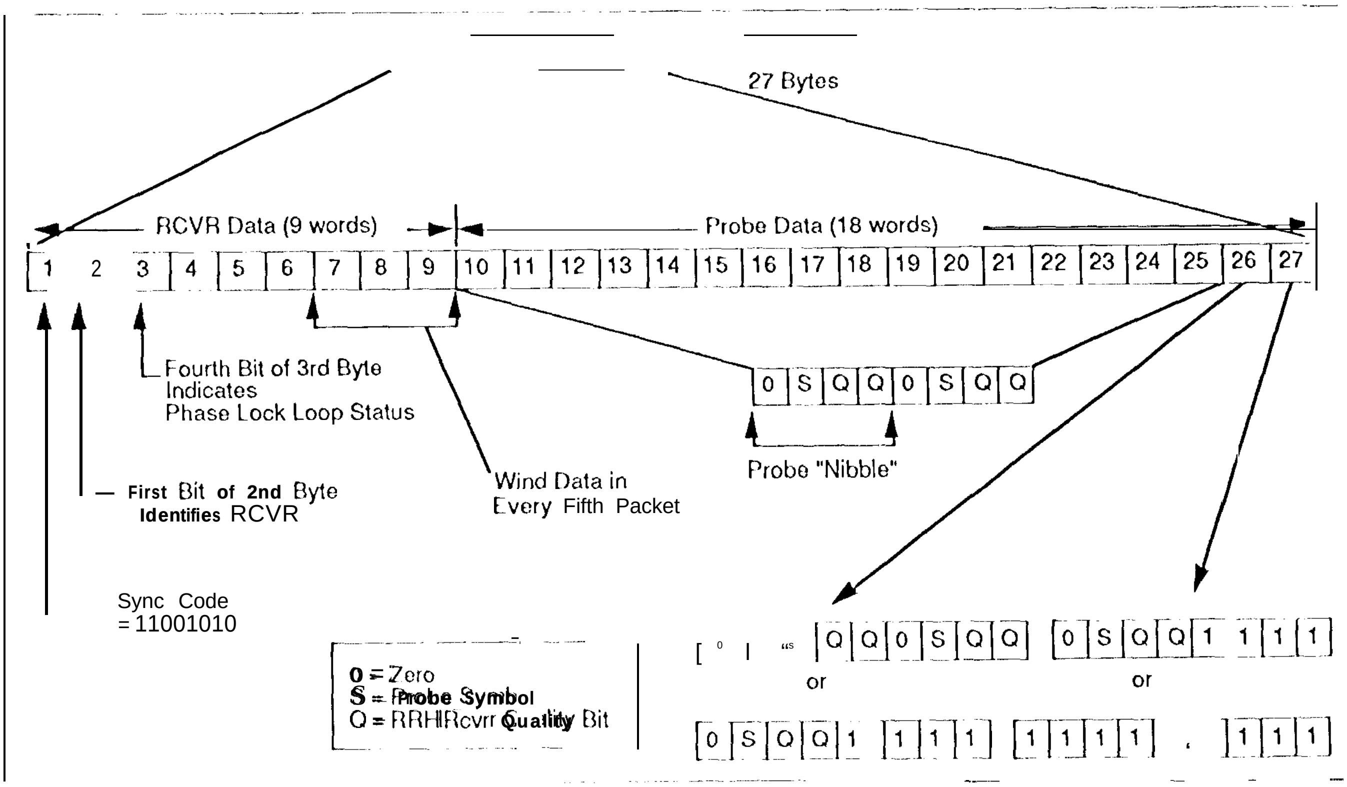


Figure 17. Probe/RRH Packet Format

DBUM, extended memory). Refer to Fig. 18.

This amount of data is sufficient to cover the. 'robe's descent to about 10 bars into Jupiter's atmosphere and is sufficient to achieve the Probe mission's primary scientific objectives.

Jupiter Approach and Io science data, including embedded engineering, will be recorded on DMS recorder tracks 2, 3, and 4 and will be saved for return using Phase 2 software. Recorder track 1 will be used to record all data beginning at IO+15 min (the lime at which the orbiter is in Relay Readiness Configuration, or RRC) and continuing until track 1 is full, about 8 hrs later. During this time period the most critical engineering activities will be occurring (Relay Configuration, J'robe Relay, Spin-Up, JOI, and Spin Down) and will be recorded. All except Relay data arc. recorded using a new 7.68 kbps LPW record format ('I'able 2) which is like the original 1 .RS format except high-rate PWS data replaces Golay data to augment the 10 torus fly-through. Probe relay data will be collected using a new 7.68 kbps LPR record format (Table 3).

Probe Relay data collection to the two destinations (DMS recorder and CDS memory) is initiated and terminated differentl y. Relay data going to the DMS tape recorder is started 6 minutes before. the, best estimate of l'robe entry time and slopped 81 minutes later via commands in the spacecraft Critical Sequence. Data going to the CDS memory is started by the. receipt of an RRH receiver in-lock bit from either RRH channel anytime after the spacecraft Critical Sequence switches the DMS record mode from the LPW to the LPR format and is stopped when the CDS memory is full.

'1'able 2. I .PW Frame

Source	Bytes
Header	96
Engineering	704
UVS	672
HIC/EUV	96
SSI Status	96
PLS	408
NIMS Status	24
PWS	432
DDS	16
EPD	400
PWS	432
EPD	208
PPR	144
MAG	80
PWS	432.
MAG	80
PWS	160
AACS	19?
PWS	432
Total:	5101

5101

8.3.2 Additional Spacecraft Functional Changes

Several additional Phase 1 spacecraft functional changes are required to perform the mission with the LGA. These include changing the HIC/EUV data readout method, lifting all CDS memory w'rile-]~rolcctiorl, and a number of fault-protection changes.

HIC/EUV data collection wiii be removed from the normal telemetry collection process to allow the HIC to buffer its data internally. Normal CDS telemetry pickup resets the HIC buffer, preventing this buffering. Readout of the HIC data will be accomplished using engineering Memory Read Out (MRO) capability described later.

Recording of Probe symbol data into the CDS extended memory requires that all CDS memory write-protec[s be li fted, since write-protect bits simultaneousl y control blocks of memory in both the non-extended and extended portions of CDS. Thus, allowing CDS [0 write into extended memory can be done only by ii fling the write.-protcCLs on all of CDS memory. This is considered to be of low risk since there has never been a CDS write-protect violation on either Galileo or Magellan so far. A risk does exist that a single-c.vent upset might occur during the highest radiation environment around Jupiter' closest approach, but analysis indicates that this risk is small,

Necessary system fault-protection changes (contained in CDS flight software) include Undervoltage Recovery (UVREC) Response., DMS Rc.cove.ry Response, Downlink Response, and AACS initialization Cruise Response (AACS_INIT) to properl y configure the spacecraft following an undervoltage event, command loss event, or AACS initialization.

Modifications to CDS internal fault protection code will also be made to allow CDS to autonomously swap the. single DMS tape. recorder to the operating CDS siring in the event a CDS siring goes down during Probe Relay. This is done

Table 3. LPR Frame

Source	Bytes
Header	96
Engineering	704
I'Iot)c/1<1<11	432
Golay	432.
l'lobe. / RRH	432
Golay	432
}'J01)C/}{1{11	432
Golay	432
Probe / RRH	43?
Golay	432
Probe / RRH	432
Golay	432
Total:	5101

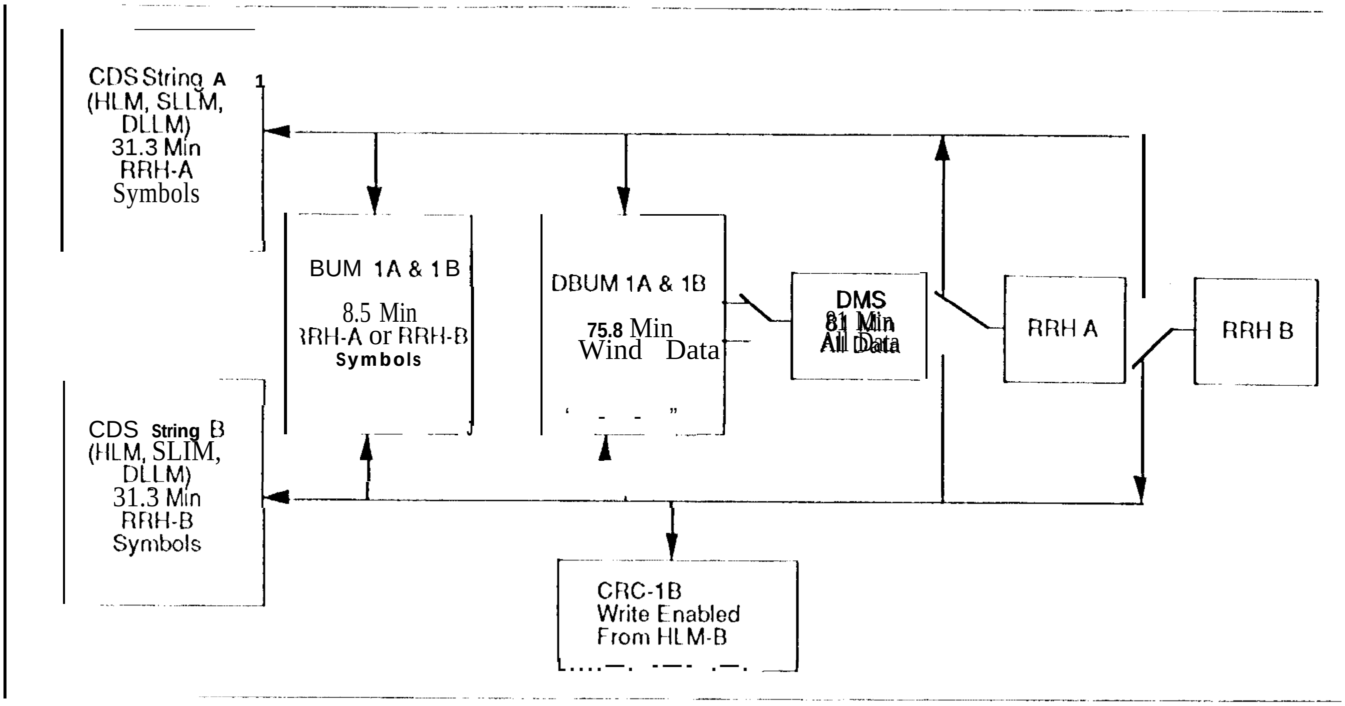


Figure 18. RRH Data Flow

by removing the CDS writer-protects on the CDS H-string spun Critical Controller, or CRC, (these are different from the CDS memory write-protects) and setting the. bits in the CRC registers so that either siring can take control of the DMS and DBUMs in the event of the loss of the, other string. The Critical Controller is directly commandable through the Hardware Command Decoder (HCD) which receives commands directly from the uplink channel without going through the CDS. Figure 14 shows the HCD to CRC flow, and Fig. 18 shows the RRH to DMS data flow.

Up until the time that Relay data is written into CDS extended memory, that memory holds redundant copies of the CDS flight software which is being executed in CDS non-extended memory, as it dots today. This "quad redundancy" in the CDS flight software, intended to protect against a 6504 memory chip failure, is lost as soon as any Probe Relay data is stored in the extended memory. In actuality, it is already lost by the start of Relay/JOI because the two-hour round-trip light time precludes a ground response which is required to swap memories.

Nell-pl-ivilcgc.(i error (NPE) handling during Relay/JOI also requires change. Plans had been 10 disable spacecraft safing response several days prior 1010 closest approach. This meant that only CDS internal errors would terminate any non-critical science acquisition sequences. Further analysis of this plan led to the realization that certain other spacecraft faults, such as AACS Heartbeat loss or several other AACS alert code.s, might result in commanding errors within the space.cmfl that, under certain conditions, might impact the Relay Readiness Configuration or lead to damage of science instruments.

Several solutions to this potential problem were examined. The chosen approach is for CDS to kill any sequences running under any one of three specific sequence IDs whenever a non-privileged error occurs, safing is disabled, and the spacecraft is executing the Critical Sequence.

8.3.3 Data Return

As discussed earlier, only Probe Relay data (and alternately real-tim engineering data) will be returned during the. Probe data return period. Jupiter Approach, Io science data, and critical sequence engineering data stored on the DMS recorder will be returned after Phase 2 software is loaded on the spacecraft in March 1996.

Probe data return is expedited by several enhancing features. These include: new 8 and 16 bps down link rates, an 80-byte memory readout capability (MRO), changes in the fixed telemetry channel allocations, operation of the spacecraft Telemetry Modulation Unit (TMU) in a suppressed carrier mode using the low-rate subcarrier, and an advanced receiver on the ground to receive it.

Additional downlink data rates of 8 and 16 bps are being added to augment the. existing 10 and 40 bps rates. The resulting set of available data rates allows for better use of available downlink channel capabilities.

To receive these data rate.s with one stand-alone 70-m Deep Space Network (DSN) station, the. spacecraft TMU will be operate.d with suppressed carrier and the low-rate (22.5 kHz) subcarrier. An advanced receiver (Block V), capable of receiving suppressed carrier signals, will be installed at each of the three DSN 70-m stations (Canberra, Goldstone, and Madrid). These changes provide approximately 5.5 dB of additional channel gain.

A new 80-byte engineering MRO capability has already been installed on the spacecraft 10 replace the original 32-byte engineering MRO. The MRO will be used to return the Probe Symbols data stored in CDS memory, to return Probe data stored on the DMS recorder, and to read out the HIC/EUV instrument self-buffered data. After the Probe symbol data in CDS memory is returned three times, the DMS recorder data will be incrementally played back into CDS memory and the 80-byte MRO capability used to return it to the ground.

Engineering fixed-telemetry data allocations are also being modified 10 make better use of the available engineering telemetry bandwidth and 10 provide. better visibility into engineering parameters of interest 10 the RRC. Engineering measurements which are no longer needed and measurements of little value except for *post facto* troubleshooting are being removed from the fixed telemetry channels to accommodate these changes. This allows measurements of more immediate interest 10 be returned more frequently by assigning them 10 multiple locations in the fixed telemetry channels. "This additionally allows the nominal engineering data rate in the downlink to be reduced to 2 bps, augmented with two 10 bps dedicated engine.crirrg passes (eight hrs per pass) per week. All other engineering measurements are. still accessible when needed by placing them in variable engineering formats.

8.3.4 Ground System Changes

The Galileo Project-Specific Ground Data System, the Multimission Ground Data System, and the DSN must make. changes 10 support the spacecraft changes described above.. These changes include support of the new 8 and 16 bps data rates, providing modified command tables for the. new record and telemetry formats, modification to the Probe Flight Operations Equipment (PFOE) 10 support the new Probe Symbols readout from CDS memory, addition of the Block V receiver to the DSN stations, and providing the DSN capability to perform Pseudo Noise. (PN) ranging to augment the ranging currently in use..

The Probe Flight Operations Equipment (PFOE) is being modified to accept the Probe symbols data, combine the three received copies obtained via the CDS MROs to produce a single "bested" copy, and 10 expand that "bested" copy into the original Probe data format. This allows the original PFOE software to process both the Probe. symbols data from CDS memory and the full Probe data set returned from the DMS recorder.

8.4 Phase 2

The objectives of the Phase 2 modifications are to: 1) increase science information density of the downlink using compression and onboard processing, 2) increase the number of downlink data rates and modes in order to utilize link capability efficiently, 3) incorporate advanced coding techniques to increase telemetry return, and 4) increase the actual or effective DSN aperture and sensitivity for Galileo.

Phase 2 involves more extensive changes to both space.craft and ground systems than Phase 1. Spacecraft systems being modified include most science instruments, CDS, and the Attitude and Articulation Control System (AACS). Ground systems being modified include most of the Galileo Project-specific ground data systems, the Multimission Ground Data System (MGDS), and the DSN. These changes allow editing and compression of the science and engineering data streams, and provide. a fairly complex buffering mechanism to manage the flow of data from real-time sources and DMS recorder playback into the downlink channel. A fundamental change from Time Division Multiplexed (TDM) downlink to packetized telemetry is also being made to make efficient use. of the. downlink channel with variable packet sizes which re.sult from varying data compression results, and to provide flexibility in selecting which data is to be included in the downlink.

Unlike Phase 1 software changes, Phase 2 software changes are complex enough that they will require bringing down CDS one string at a time while the new flight software is loaded. AACS software changes can be patched into the on-line and off-line. memories without interrupting normal AACS operations.

8.4.1 Spacecraft Software Changes

Figure 19 provides an overview of the new Phase 2 spacecraft software.

Eight out of eleven science instruments are being modified to change their functionality to be compatible with the new spacecraft capabilities. DDS, EPD, EUV, MAG, NIMS, PLS, SSI, and UVS all require flight software changes; HIC, PPR, and PWS do not. Details of the changes to the science instruments are beyond the scope of this paper.

New capability is being provided in CDS to collect data from each of the modified science instruments, to edit (i.e., throw away some of) each data stream, to assemble the data into packets, to assemble packets into Virtual Channel Data Units (VCDUs), and to store those VCDUs in a multi-use buffer for later downlink. Figure 20 shows the structure of packets, VCDUs, and Frames (which will be discussed later). Table 4 shows the eight Virtual Channel ID assignments.

Beyond the process of collecting the data into VCDUs as described above, certain additional instrument-specific processing is being added to the CDS or the AACS. Real-time data stream processing, (editing, summing, or other instrument specific processing) is being provided for NIMS, UVS, MAG, PLS, EPD, DDS, HIC, PWS low-rate, and SSI (for Optical Nav only, as described later). DMS tape recorder playback processing is being provided for SSI (all images), NIMS, PPR, UVS, and PWS high-rate.

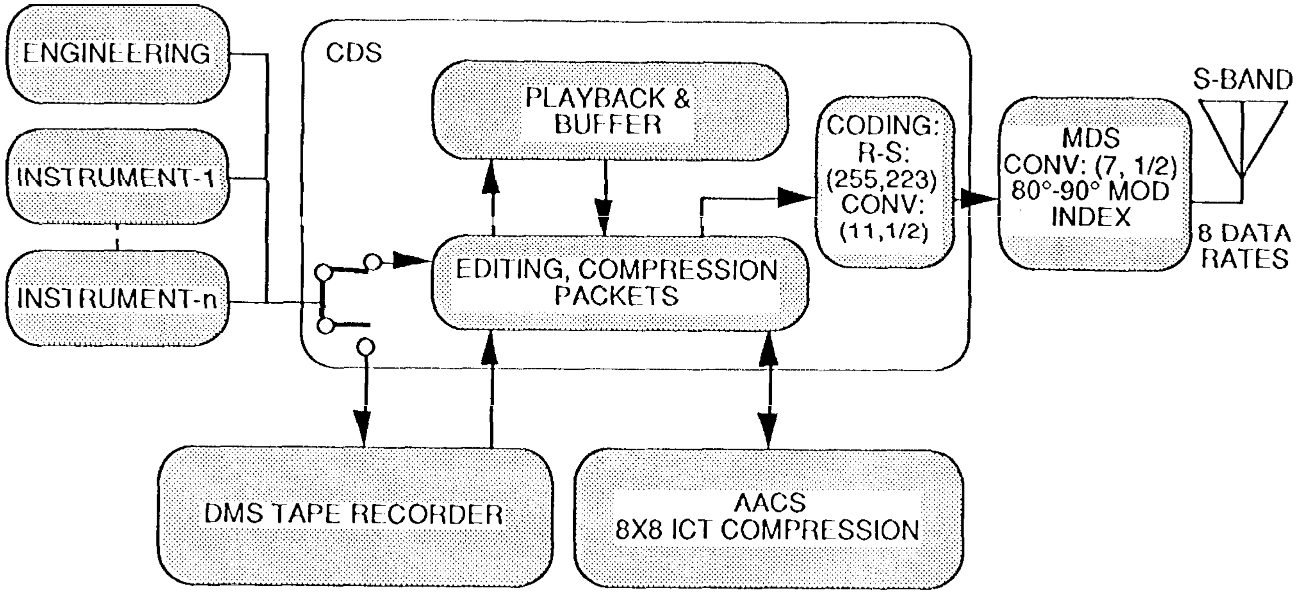


Figure 19. Phase ? Spacecraft Design Overview

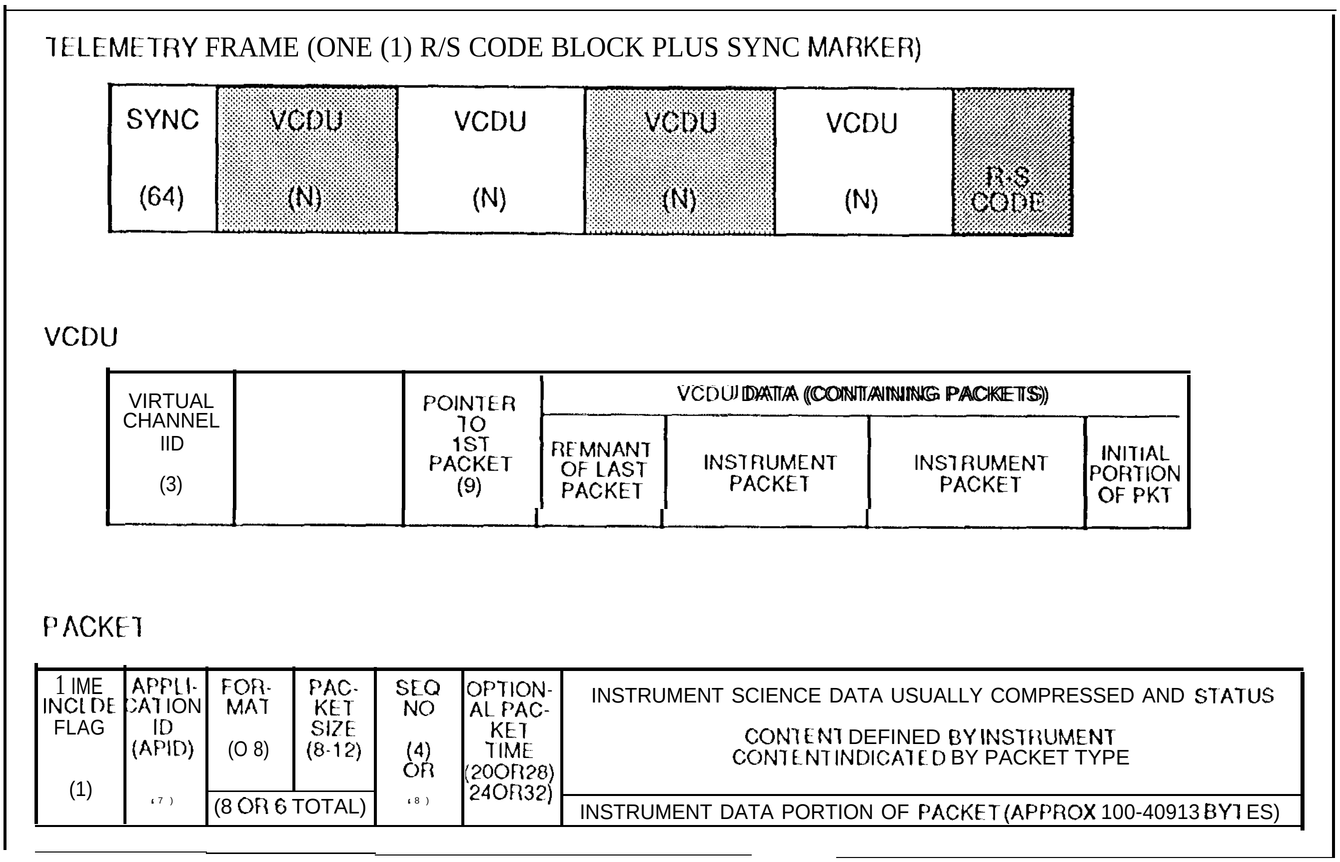


Figure 20. Galileo Packet Telemetry Data Structure

'1'able 4. Virtual Channels

VCDU ID	VCDU TYPE
000	Priority Data (Engineering and OPNAV)
001	Real Time Science (1<"1'S), Burst to Buffer
010	Playback Data. Burst to Tape
011	Record Rate Change Data
100	Spare
101	Buffer Dump to Tape. Real Time Science (1{"1'S)
110	Buffer Dump to Tape. Playback Data
111	Buffer Dump to Tape. Record Rate Change Data

Data compression is being provided in two forms. First, an 8x8 Integer Cosine Transform (ICT) compression algorithm is being implemented in the AACS as a background task that will process PWS low-rate data in real-linw and will process SS1 playback images fast enough to keep up with the 7.68 kbps DMS recorder playback rate. Two additional modes of the algorithm will allow lossless compression using a Huffman algorithm, or will allow the data to be returned to CDS without being compressed. One limitation which results from doing the compression in the AACS is that AACS must suspend processing of the gyro and accelerometer data in order to have the time available to support the compression processing.

Secondly, NIMS playback data will be losslessly compressed try CDS using the Rice algorithm (Ref. 1 0).

Lossless compression, although originally planned for all mri-lime and playback low-rate science data, was removed from the design (except for SS1 and NIMS as mentioned above.) in preference for higher priority science processing capabilities which were competing for the same. available memory resources.

The ICT compression algorithm is "lossy" in the sense that some information in the original data stream will be lost The ICT will compress SS1 images to achieve target compression ratios of between 5:1 and 40:1.

Actual compression ratios obtained for SS1, PWS, and NIMS will depend upon the characteristics of the images being compressed, making the actual amount of data produced by processing the raw data from each of these instruments variable and somewhat unpredictable. This variability is easily accommodated by the new variable-length packets.

A new Optical Navigation (OpNav) capabil it y is being provided which will yield OpNav images edited to reduce the volume of data required to return the image by a factor of 300 to 500. This method (Fig. 21) locates the limb and terminator of a Jovian satellite by taking strips along the expected location of the moon, computing the centroid of the satellite, and then collecting 2.0x20-pixel square regions arou nd preselected offsets from this centroid where target stars arc expected to be located. These mail portions (strips and square.s) of the SS1 frame arc returned to tile. ground and reconstructed into a standard OpNav frame by the Multimission Image Processing System (MIPS). This OpNav algorithm can operate on either real-(imc SS1 images or on recorded images.

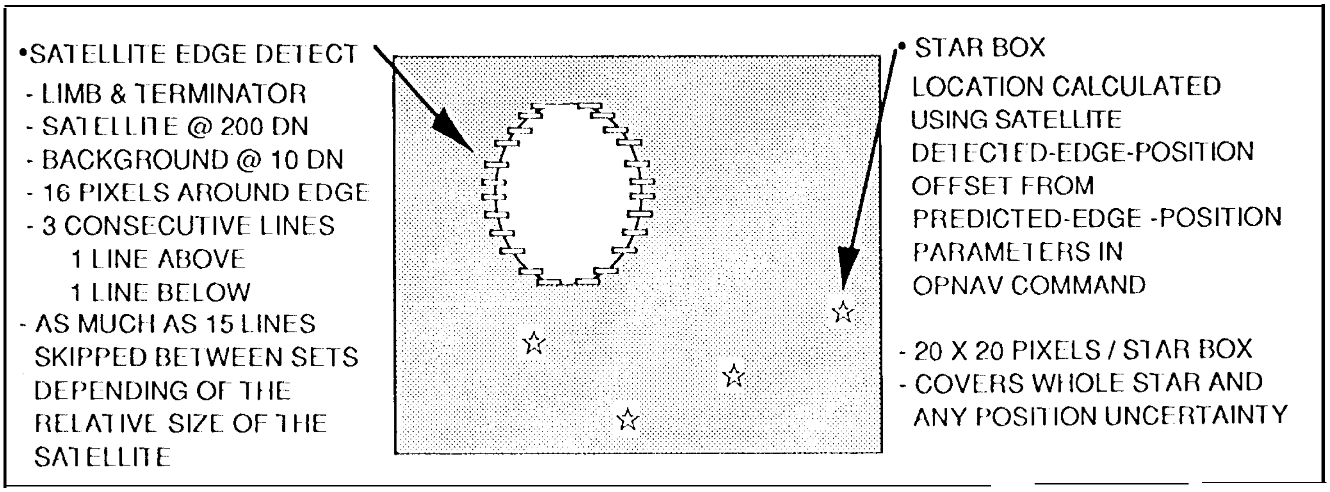


Figure 21. Optical Navigation Editor

During encounters and at other selected times during cruise between encounters, data will be collected from the instruments and stored on the DMS [ape recorder for later processing. Processing of data from the DMS recorder playback includes new capability to identify recorded data by source, perform lossy ICI' compression on SS1 data in rc.al-lime during playback using the AACS computer as a co-processor, and store other playback raw data into the multi-use buffer for later CDS processing. This other playback data in the buffer will be edited, packetized, assembled into VCDUs, and stored in the multi-use buffer for later downlink. The design includes the capability to deselect any data on the recorder during playback.

Fifteen record formats (8 old, 7 new), and nine real-time formats are being provided to support the new mission capabilities. Although dc.tailed descriptions of these formats are beyond the scope of this paper, Table 5 shows the 15 record formats with brief descriptions of their function, and '1'able. 6 shows the nine mrl-time. science formals, their bit rates, and the allocation of (hose bit ram to individual science instruments. Capability is provided for deselection of any data from both the real-lirnc and record data streams.

Two other special data-handling functions are also provided. These arc Buffer Dump 10 Tape (BDTT) and Record Rate Change Coverage (RRCC).

BDTT is used for planned downlink outage periods to allow maximum continuity of real-time low-rate science collection. During these, planned downlink outage, periods, when the buffer fills up, it is dumped to the DMS tape rcc.order. Separate VCDUs arc used to hold this data to allow easy merging with other rc.al-time data once this data is returned to the ground, which may be many weeks later than real-tinlc data which was not dumped to tape.

RRCC is used during DMS record rate change.s. When the tape rc.corder mode changes such that the. rate that data is being placed on the DMS changes, up to several seconds of record data would be lost without this capability. The RRCC builds a VCDU continuing data during this change period and inserts it into the multi-use buffer for downlink with the real-time data. Thus, this data might arrive weeks ahead of related data that was stored on the DMS tape recorder. The separate VCDU allows this data to be easily flagged for merging with the DMS rc.corder data when it is finally downlinked to the. ground.

All data, whether real-time, DMS tape recorder playback, or one of the three special functions, eventually ends up as VCDUs in the multi-use buffer. As downlink capability allows, a Frame Builder in the CDS Reed-Solomon encodes and assembles these VCDUs (four at a time) into 20-18 byte frames. These frames arc. passed though a software convolutional (1 1,1/2) code.r in the. CDS before being passe.d to the Telemetry Modulation Unit (TMU) in the Modulation Demodulation Subsystem (MDS) where the data is hardware convolutionally coded (7, 1/2), yielding an effective (14, 1/4) convolutional code, and passed 10 the Radio Frequency Subsystem (1<} 'S) for downlink to earth at S-band frequencies (roughly 2 GHz) via the spacecraft's 1 .GA.

As in Phase 1, the TMU is operated with no residual carrier and with the low-rate (22.4 kHz) subcarrier.

Downlink is accomplished at one. of eight fixed telemetry data rates. These rates, measure.d after the Reed-Solomon encoding but before any of the convolutional encoding, arc 8, 20, 32, 40, 60, 80, 120, and 160 bits per second (bps). The symbol rate in the downlink channel is four times the. data rate, due. to the (]4,]/4) convolutional encoding. Rates available for inclusion in this set were limited by the. CDS hardware and the chosen frame size. This particular set was chosen to provide. the ability 10 utilize roughly 85 percent of the. theoretical downlink channel capability over the life of the. mission.

As shown in '1'able. 7,90 different CDS Telemetry Modes provide a variety of combinations of one of the. nine real-lirnc science formats and onc of the two engineering data rates (2 bps or 10 bps) for each of the eight telemetry bit rates with the balance of the bps capacity used to downlink tape playback data. Downlink rates that arc, slower than the collection rates (columns 3 or 4 larger than the telemetry rate) tend to fill the multi-use buffer; downlink rates that arc greater than the collection rate.s (columns 3 or 4 less than the telemetry rate.) tend to empty the buffer. Deselection of an instrument from the real-time telemetry stream shifts this balance. in favor of emptying the buffer.

The long-term average collection rates after onboard processing must be close to being equal to the long-term average downlink r-ate. This Iong-term averaging must be controlled by the ground sequence designers. If the collection rate is too iow, downlink capability is wasted. If the collection rate is too high, the data cannot all be returned. New ground system tools are being developed which wiii allow sequence designers 10 mode.1 and optimize the balance of collection vs. downlink capabilities when designing each and every spacecraft encounter and cruise sequence.

The original spacecraft design provided fully redundant subsystem elements for all mission-critical functions. This redundancy is retained for all except the new capabilities described in this paper, which are not redundant. Should a CDS or AACS failure occur, execution of the new capabilities wiii be suspended anti new software loads wiii need 10 be designed, developed, and loaded onto the. spacecraft in order to continue with the collection of science data. Safety of the spacecraft will, however, be assured through the existing subsystem redundancy and existing fault-protection software.

Two other minor changes arc aiso being made to the space.craf~ software. The tlo-byte. MRO provided for [he. Phase 1 portion of the mission wiii be restored to the original 32-byte MRO formal. Additionally, fixed telemetry channels wiii be reassigned, as they were in Phase 1, [0 provide improved visibility into the operation of the new' Phase 2 capabilities. These include variables for uplink command verification and for monitoring the state of the multi-use buffer.

Table 5. Record Formats

Mnemonic	Status	Function
LNR	NEW	7.68 KB/S RECORDING OF NIMS LRS DATA
LPW	EXISTING (FROM 01)	7.68 KB/S RECORDING OF PWS AND LRS DATA
LPU	NEW	7.68 KB/S RECORDING OF NIMS PLUS UVS & P]'
MSL	NEW	28.8 KB/S RECORDING OF SS1, & LRS DATA
IM8	EXISTING	806.4 KB/S RECORDING OF SS1, NIMS, LRS
A18	EXISTING	806.4 KB/S RECORDING OF SS1, NIMS, LRS DATA
HIM	EXISTING	115.2 KB/S RECORDING OF SS1, N] MS, LRS
HPW	EXISTING	806.4 KB/S RECORDING OF SS1, N] MS, LRS
MPW	EXISTING	28.8 KB/S RECORDING OF SS1, NJ MS, LRS
111'"1' (PPR BURST MODE TO TAPE)	NEW	7.68 KB/S RECORDING OF PPR DATA BURST MODE BUFFER
MPP	EXISTING	28.8 KB/S RECORDING OF PWS & LRS DATA
IM4	EXISTING	403.2 KB/S RECORDING OF SS1, N] MS, LRS
BDT	NEW	7.68 KB/S VCDU DATA FROM MULTI-USE BUFFEI
1ICA	NEW	115.2 KB/S NIMS, LRS, & SS1 DATA
1IMA	NEW	114.2 KB/S NIMS, LRS, & SS1 DATA

Table. 6. Science Formats

Format	Total Real-Time Science Data Rate**		MAG	EPD	PLS	PWS	DDS	HIC**	EUV**	UVS	NIMS	AACS
	w/ HIIC	w/ EUV										
A	19.7		2	5	5	5	1.1	1	0	0.2	0	0.4
B	20.7		2	5	5	5	1.1	2	0	0.2	0	0.4
C	30.8	30.8	2	5	5	5	3.4	5	5	5	0	0.4
D	32.8	40.8	2	5	5	5	3.4	2	10	10	0	0.4
E	59.8	67.8	4	10	10	10	3.4	2	10	10	10	0.4
F	66.8		6	15	15	15	3.4	2	0	10	0	0.4
G	91.8	91.8	8	20	20	20	3.4	5	5	5	10	0.4
H	117.8		12	30	30	30	3.4	2	0	10	0	0.4
I	151.8		16	40	40	40	3.4	2	0	10	0	0.4

** HIC and EUV cannot both be included in a format at the same time, and one or the other will always be deselected.

'1'able 7. Phase 1 Ground System

ENG (bps)	RTS Format	Eng, RTS, and AACS Combined Telemetry Rate* w/// HIC	w/ EU\	0	8	20	32	40	60	80	120	160
				1 elemetry Rates (bps)								
2	A	25.0			AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8
2	B	26.1		BL0		BL2	BL3	BL4	BL5	BL6	BL7	
2	c	37.9	37.9		CL1	CL2	CL3	"-"cl 4	c1 5	CL6	CL7	CL8
2	D	40.2	49.5			DL2	DL3	DL4	DL5	DL6	DL7	
2	E	71.6	80.9	EL0	EL1	EL2	EL3	EL4	EL5	EL6	EL7	EL8
2	F	79.8			FL1	FL2	F-13	FL4	FL5	FL6	FL7	FL8
2	G	'108.9	108.9			GL2	GL3	GL4	GL5	GL6	GL7	GL8
2	H	139.1				HL2		HL4	HL5	tIL6	HL7	tIL8
2	I	178.7					11.3		IL5	IL6	IL7	IL8
10	A	33.2			AH1	AH2	At I3	A H 4	AH5	AH6	At I7	AH8
10	B	34.4		BH0								
10	C	46.2	46.2		CH1	CH2	cl I3	CH4	CH5	CH6	CH7	ct,18-
10	D	48.5	57.0									
10	E	79.9	89.2			EH2	EH3	EH4	EH5	EH6	EH7	EH8
10	F	88.1										
'-lo	G	117.1	117.1									
10	t{	147.4										
10	I	187.0										
40	B	65.5						BA4		BA6		
TOTAL TELEMETRY MODES: 90												

'Combined telemetry bit rate includes engineering data editing (1 : 0.89), packet overhead (1 : 1.018), and R-S overhead (0.875:1).

Engineering data rate is a collection rate, RTS and AACS data rates are after all editing and compression algorithms have been applied.

1 elemetry bit rates are counted after frame construction and contain RS overhead.

8.4 .?. Ground System Changes

Figure 22 shows a high-level overview of the Ground Data S ystem (G I) S). This system is made up of Galileo I'frrjcc[-specific GDS (PGDS), the MGDS, and DSN elements.

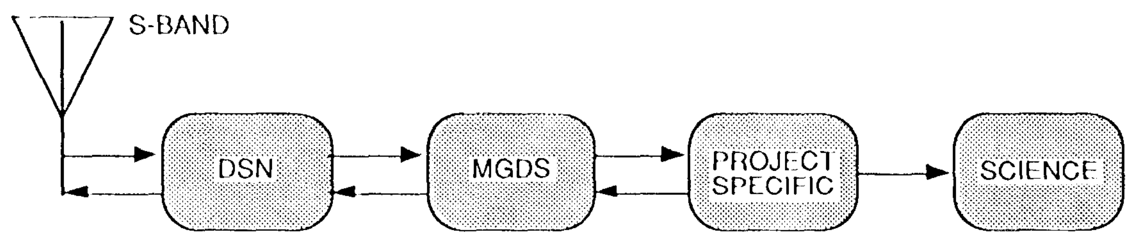
All elements in the GDS must accommodate the new data rates and the new packet telemetry format which replace the TDM formats used up until the. Phase 2 software is uploaded. The original TDM modes for 10 and 40 bps arc retained to accommodate communications in a spacecraft fault-recovery condition.

All elements of the, GDS must also accommodate a guaranteed delivery system of data transfer through the GDS network elements. 'Ibis guaranteed delivery system is expected [0 utilize a standard protocol, which will reduce network errors 10 less than onc in 10'. This iow error rate is necessary to achieve the overall downlink error rates needed to accommodate the planned use of data compression.

The PGDS m ust provide tools and procedures needed to o~)c.rate the new spacecraft capabilities. These include new prediction tools which will allow sequence designers to predict the Condition of the multi-use buffer anri to manage the DMS recorder tape allocation. These tools arc needed to ensure that sequences for the spacecraft collect oniy so much data as can be fit into the available downlink. This overall downlink capability varies daily as the rotation of the Earth brings different DSN antennas into spacecraft viewing position with each orbit, since orbits arc of different duration, and with ihc spacecraft-to-Harh range which varies because of the Earth's motion about Lilt Sun, Table 1 shows these parameters for each of the Jovian planetary encounters.

Additionally, the PGDS provides the commands necessary to operate the new spree.craii capability and provides the downlink software necessary to process and distribute the data 10 the end users of that information.

The MGDS wiii implement the decoders and decompressors needed to invert the processes used on the spacecraft. Specifically, a convolutional decoder must be provided 10 accommodate the (14, 1/4) code while retaining the NASA standard (7, 1/2) code which is used for the two TDM modes invoked during fault-protection response., a



[EN:
- S-BAND ULTRA CONE AT CANBERRA
- ADVANCED DIGITAL RECEIVERS AT ALL STATIONS
- FULL SPECTRUM COMBINER AND FULL SPECTRUM RECORDERS AI" EACH SITE FOR GAP FILLING
- ERROR-CORRECTING DECODER (14, 1/4 VITERBI, DEPTH 8 R-S)
- ACCOMMODATE UP TO 6 DATA RATES PER PASS

MGDS:
- ACCOMMODATE GALILEO PACKETIZED TELEMETRY
- IMPLEMENT NEW TELEMETRY FORMATS
- 1 LM DECODER & LOW-RATE PWS DECOMPRESSOR
- MULTIMISSION IMAGE PROCESSING SYSTEM (MIPS) -PACKETS, OP-NAV EXPANSION, AND SSi & NIMS DECOMPRESS1ON

PROJECT-SPECIFIC:
- PACKET TELEMETRY PROCESSING
- COMMAND DATA BASE NEW COMMAND DEFINITIONS
- SEQUENCING FOR NEW SPACECRAFT CAPABILITIES

SCIENCE:
- SCIENCE VAX CLUSTER-SPICE ACCOMMODATION OF NEW TELEMETRY

Figure 2?. Phase 2 Ground System Design Overview

Reed-Solomon decoder which can handle the interleave depth eight and variable-length redundancy codes used in each downlink frame, and a decompressor must be provided for the ICT and Rice compressors. These will allow the MGDS to deliver decoded and decompressed data to the PGDS.

The DSN requires several changes to support the new communications capabilities. These include new receivers capable of receiving the suppressed carrier signals from the spacecraft, enhanced S-band reception, the ability to array multiple antennas, and 1'scrr(io-Noise () 'N) Ranging.

Two approaches to advanced receivers are being pursued in parallel. Both will be provided to support the Orbital Operations mission.

The first of Lime is a new Block V receiver (IIVR), which is an all-hardware digital receiver, followed by a symbol combiner to effect arraying. This receiver is installed at each DSN antenna and is capable of locking onto and tracking the carrier and/or subcarrier and symbol streams in the downlink data, with or without a carrier being present. The second approach is a software digital receiver called a Full Spectrum Combiner (FSC) located at the Canberra complex coupled with a Full Spectrum Recorder (FSR) located at each station.

These two advanced receiver approaches process the received signals differently. The BVR approach uses the full spectral content of the incoming signal at each station for signal detection and uses post-detection combining to accomplish arraying of signals from multiple antennas. Since it depends upon valid symbol streams from each BVR to effect combining, loss of BVR lock for any reason results in gaps in the data.

The FSR/FSC approach uses pre-detection combining of signals from each antenna, but only uses the first four harmonics in the signal from each antenna. The FSR provide.s recording of the signals from each antenna prior to detection, providing the capability to fill in gaps which occur during the signal acquisition process.

The BVR will be used for normal production processing of received data and the FSR/FSC will be used to fill in any gaps in the BVR data,

Enhanced S-band reception is being provided by the installation of an S-band ultracone on the Canberra 70-m antenna. This ultracone lowers the Canberra 70-in noise temperature from 13.6°K to 10.5°K, providing roughly 1.1 dB improvement in the channel performance on the antenna with the longest space<.rafl view period (about 12 hrs daily).

The nominal DSN antenna configuration will change during the mission. During the first orbit, oniy the three 70 m antennas will be available. The ultracone will become available at Canberra just before the G 1 orbit. For the remainder of the mission, the three 70 m antennas, the ultracone at Canberra, three Canberra 34-m antennas (STD, HEF, and BWG), including the requisite intra-site arraying, and Goldstone-Canberra arraying will be provided.

9. Summary

The Probe Data Protection and the Orbital Operations require substantial changes to both spacecraft systems and ground systems in order to accomplish the Galileo mission using the severely limited downlink capabilities of the LGA. These capabilities, which are. now well along in development, are expected to enable the accomplishment of at least 70 percent of the original scientific objectives of the Galileo mission.

10. Acknowledgments

The design described in this paper represents the combined efforts of hundreds of scientists, engineers, anti support personnel, without whose effort the many concepts and compromises needed to achieve these designs would not have been possible.

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